R.S. McKamey

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TURBINE ENGINE MATHEMATICAL MODEL VALIDATION

ENGINE TEST FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

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APPROVAL STATEMENT

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20 ABSTRACT (Continue on reverse side if necessary and identify by block number) This report presents and discusses the results of an investigation to develop a rationale and technique for the validation of turbine engine steady-state mathematical models for use in predicting flight test performance, stability, and durability parameters. A validation procedure is derived and demonstrated using the YJ101 prototype engine AEDC test results and status deck as an example application of the technique. Typical status deck uncertainties		

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20. ABSTRACT (Continued)

as a function of flight condition, engine power setting, and deck input parameters are given. Status deck flight test input error effects are also given.

PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65807F. The results of the research were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee, under ARO Project Number R43G-05A. The author of this report was Lex Hutcheson, ARO, Inc. The manuscript (ARO Control No. ARO-ETF-TR-75-163) was submitted for publication on November 20, 1975.

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1.0 INTRODUCTION

Past operational evaluations of USAF aircraft and propulsion systems have shown the need for improvements in the accuracy of propulsion system performance determination procedures. An accurate prediction of engine and propulsion system performance is necessary to assess overall aircraft systems performance. In order to improve these procedures, prediction methods must be systematically updated during development with verified engine characteristics over a key range of mission-oriented flight conditions, with a high degree of certainty.

Techniques for measuring turbine engine performance at simulated flight conditions have been developed in the ground test facilities of the Engine Test Facility AEDC (ETF), Ref. 1. These AEDC-developed techniques provide order-of-magnitude improvements in measurement uncertainty over that available a decade ago. In addition, sophisticated turbine engine mathematical models have been developed by the Air Force and various turbine engine manufacturers (Ref. 2), and these models have become the standard practice for the communication of engine performance predictions among the various systems developmental agencies. The turbine engine math model is now being used during development and test programs to define installed engine performance characteristics and as an aid in determining overall aircraft system performance. As of the present time no known orderly procedure has been established to validate the use of this technique or to quantify the uncertainty of math model predictions over a defined range of key mission flight conditions.

1.1 OBJECTIVES

The objectives of this project are to establish an orderly methodology for the validation and determination of uncertainty in turbine engine math models. The General Electric (GE) YJ101 engine, propulsion subsystem for the Northrop YF-17 aircraft, was used as an example for this report. The scope of the effort to be reported herein includes the following steps: (1) development of a validation rationale and technique, (2) validation of the YJ101 status deck, and (3) determination of YJ101 status deck uncertainties as a function of input parameters.

1.2 ENGINE TESTS AND STATUS DECK

One prototype YJ101-GE-100 engine (S/N 214005-1B) was tested at the Engine Test Facility (ETF), Arnold Engineering Development Center (AEDC), at simulated flight conditions ranging from sea-level static to 60,000 ft altitude, Mach number 2. The AEDC altitude testing was conducted during the period from August through December 1973, to determine engine performance, stability, and mechanical characteristics.

Following engine tests the manufacturer (GE) produced a test-adjusted math model status deck (No. 74017A) to be used during the lightweight fighter prototype flight test program. This status deck was adjusted to be representative of the sea-level-static performance of the family of six early flight test prototype engines (S/N's 214005 and 214101 through 214105), and the AEDC altitude performance of engine S/N 214005-1B. The validity of status deck 74017A will be assessed herein as compared to the family of YJ101 prototype engines mentioned above and will be presented as an example of the application of the validation technique developed during this study.

2.0 APPARATUS

2.1 YJ101-GE-100 ENGINE

The YJ101-GE-100 engine is a two-spool, low bypass, augmented turbojet in the 15,000-lbf thrust class. The engine consists of a three-stage low pressure compressor (LPC) and a seven-stage high pressure compressor (HPC), each driven by a separate single-stage turbine. The engine has an annular combustor, an afterburner with a swirl-type flameholder, and a convergent-divergent type variable geometry exhaust nozzle.

The fuel control converts power lever angle (PLA) into high pressure compressor demand speed with low pressure compressor topping limit override, both as functions of compressor inlet temperature (T2). The low pressure turbine exit temperature (T6) is controlled by varying the exhaust nozzle throat area (A8), unless the minimum exhaust area or maximum turbine discharge temperatures are encountered. Turbine exit temperature limit is scheduled as a function of compressor inlet temperature. Minimum exhaust area is scheduled as a function of power lever angle, with a maximum set value for afterburning. For maximum augmented power the ratio of augmenter fuel flow to burner inlet pressure (WFAB/PS3C) is scheduled as a function of minimum exhaust area and compressor inlet temperature. Maximum compressor discharge pressure and minimum fuel flow limits are observed to ensure safe engine operation. A schematic of the YJ101-GE-100 showing the performance station nomenclature used in this report is shown in Fig. 1.

2.2 TURBINE ENGINE STATUS DECK DESCRIPTION AND USAGE

The overall relationship of the engine status deck to engine development and usage is depicted schematically in Fig. 2. The engine manufacturer develops the status deck and refines it to agree with development test data The deck can then be used by the Air Force for altitude development and test verification procedures. In later phases of development, a verified status deck can be transmitted to the flight test activities. Significant potential exits after development for the continued use of the status deck throughout the life of the engine in an aircraft system.

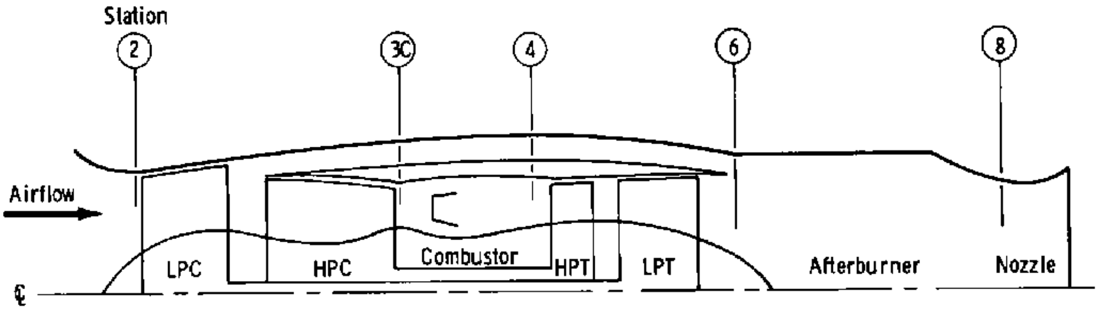


Figure 1. YJ101-GE-100 schematic.

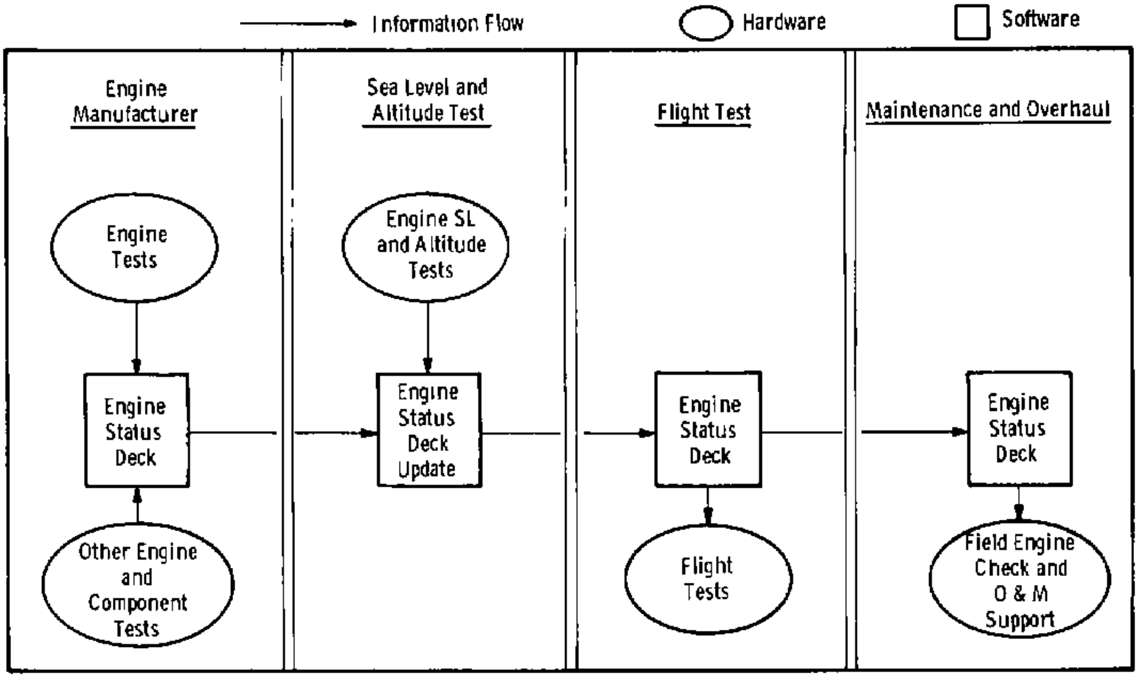


Figure 2. Engine status deck scenario.

2.2.1 Status Deck Development

Historically, the engine manufacturer has created a mathematical model of an engine long before any actual hardware is produced. This early design tool is called a preliminary design deck (see Fig. 3) and consists of the best estimates of component performance available at the time of incorporation into the math model. Output from the preliminary design deck may be transmitted to several aircraft manufacturers to aid in aircraft design concept studies and proposals to prospective government and civilian customers. A preliminary design deck may change several times before the first hardware is cut, typically from two to five years after the initial math model is developed.

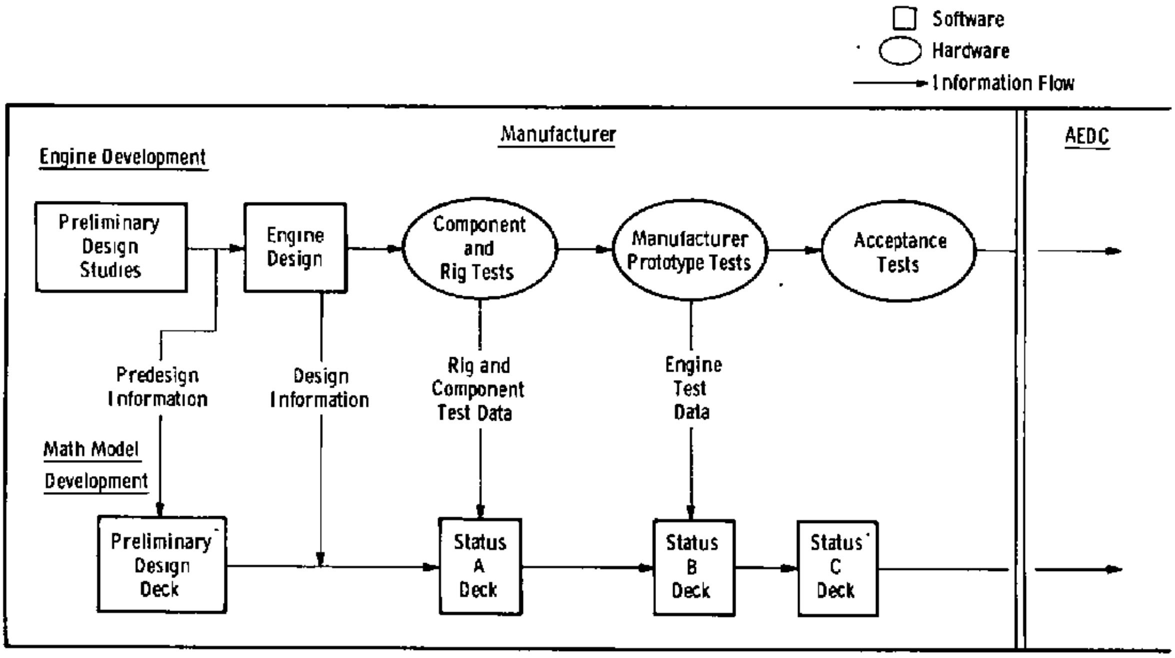


Figure 3. Engine/math model development by manufacturer.

When the engine manufacturer is awarded a contract to develop an engine and the details of the contract are negotiated and finalized, an engine design is configured and an engine deck is produced to represent the design levels of engine performance targeted for the system development.

As the building and testing of hardware proceeds, a "bank" of component and engine test information is accumulated. As the development proceeds, status decks depict the current status of the engine and components under development. The status deck will change often as hardware refinements are made, tested, and verified. The discussions and study performed under this project necessarily will be limited to the category of status decks and their degree of representation of a particular engine or family of several engines.

Industry definitions and capabilities of the three types of turbine engine steady-state mathematical models are presented by Society of Automotive Engineers documents (Refs. 3 and 4).

2.2.2 Status Deck Inputs

Status deck inputs are generally more flexible and numerous than those allowed in some final design deck where minimum inputs would be altitude, Mach number, and power lever angle. Math model inputs generally fall into three categories: (1) flight conditions, (2) engine power and geometry settings, and (3) aircraft installation effects.

For the typical status deck, flight conditions are input by one of two methods. First, the aircraft inlet and ambient conditions designated by altitude, Mach number, deviation from standard-day temperature, and inlet ram recovery may be input. The ram recovery is usually assumed to be as specified by MIL-E-5008D, or as a set of data where ram pressure recovery varies as a function of engine inlet-corrected airflow and flight Mach number. Second, the engine face total pressure and temperature and the ambient pressure and temperature may be input. This input set is analytically complete since altitude is determined from ambient pressure, deviation from standard day is determined from ambient temperature, Mach number is determined from engine face total temperature and ambient temperature, and ram recovery is determined from Mach number and engine face total pressure.

Typical status deck inputs for engine power and geometry settings may be all combined into one input, the power lever angle (PLA), which is desirable, if available. However, with the complexity and flexibility of modern turbine engine control systems, a "nominal" control is not normally encountered, and the control schedule limits may be purposely varied with different engine control trims according to test objectives. Accordingly, the engine power may be specified by appropriate basic parameters which may be used to define engine airflow rate, gas generator characteristics, and bypass ratio for a turbofan engine. For defined inlet pressure and temperature, fan and/or compressor speeds can be set to obtain airflow rates consistent with compressor geometry schedules. Engine power for the gas generator is usually determined, with airflow rate and fuel flow rate (PLA), from either high pressure compressor speed or turbine inlet (or exit) temperature. There may also be high compressor inlet guide vane geometry inputs and exhaust nozzle area inputs to complement the others. In the case of a turbofan engine, fan pressure ratio or exhaust nozzle areas may be input to determine bypass ratio. Some decks will also allow iteration to a specified value of net thrust.

Typical installation effects inputs include inlet conditions, horsepower extraction, customer bleed, exhaust nozzle configuration, and others. Naturally, any and all of these effects which can be defined should be input to the deck where appropriate and where allowed by the deck logic. A general discussion of the various types of math models is presented in Ref. 5.

2.2.3 YJ101-GE-100 Status Deck

The YJ101-GE-100 status deck (No. 74017A) is a steady-state, cycle-matching digital computer program with steady-state fuel control representation. This deck conforms to SAE Aerospace Standard 681C (Ref. 3). A description of the deck is found in the program user's manual (Ref. 6). This status deck allows inputs to be made for all controlled variables except afterburner fuel flow ratio, thus allowing off-schedule conditions to be simulated. Flight condition inputs may be made in the form of altitude, Mach number, and ambient temperature deviation from standard day, or compressor inlet pressure and temperature and ambient pressure and temperature. Inputs are also allowed to specify the customer air bleed as a rate or as a fraction of high compressor flow, and horsepower extracted may be specified within given limits.

3.0 PROCEDURE

The uses of the typical turbine engine math model status deck will influence the rationale for validation. In most cases a status deck is to be used in test evaluations, especially in predicting expected engine performance at typical flight conditions. Typical parameters of interest include fuel flow rates, compressor rotor speeds, compressor discharge pressures, turbine inlet temperatures, net thrust, specific fuel consumption, and compression system pressure ratios, as well as their respective changes with respect to flight conditions and power settings. The parameters selected for analysis and the math model validation rationale and procedure developed and used during this study are described below.

3.1 MATH MODEL VALIDATION RATIONALE

For the purposes of this study, validation is defined as the comparison of predicted math model information with the equivalent test information, in an orderly manner. In working with any math model status deck, one must assess the areas of validity and the quality of predictions within those areas. It should be decided which engine or group of engines the particular deck represents and how much actual sea-level and altitude test information is available from those engines, to be factored into the deck maps. In addition, it must be determined whether controls functions are included with the engine cycle representation and which controls inputs the deck will accept. Then, representative samples of key mission-related test conditions and power settings must be selected for examination since detailed examination of the entire flight envelope cannot be accomplished in a timely manner.

A tabulation of procedures into an orderly format to allow a rational examination has been developed and is presented in Figure 4. The categories of engine and data status (rows) shown in the figure separate the engine families and available test information into seven groups ranging, for example, from the case of many operational production engines and little available test information, to the case of one development engine with complete altitude test information available. In all cases spread would be expected from engine-to-engine and day-to-day variations, and the ability of a model to predict altitude performance will incur larger uncertainty. These predictions will be on the order of ±15-percent uncertainty, for example, while in the case of one engine and much data a status deck prediction uncertainty can reasonably be expected on the order of ±1 to 2 percent. The intermediate categories will allow potential prediction uncertainties ranging between approximately 2 and 15 percent. It is also probable that all the uncertainties are dependent upon which flight conditions and/or engine powers are under consideration, and what level of engine deterioriation has occurred.

Engine and Data Status	Status Deck Input Mode	Expected Status Deck Uncertainty 1	2	3	4
		M, ALT, No Control Definition	More Definitive Deck Inputs		P2, T2, po, to, Full Control Definition
Many (1000) Production Engines	No Current Data	(Order of ~ 15 percent)	Decreasing Uncertainty Expected		
	ALT Test Data				
Several (100) Flight Test Engines	No Current Data	Decreasing			
	ALT Test Data				
A Few (10) Prototype Test Engines	No Current Data				
	ALT Test Data				
A Single (1) Development Engine	ALT Test Data				(Order of ~ 1 percent)

Figure 4. Math model validation rationale.

The status deck input modes (columns) show in Fig. 4 illustrate the different test measurement inputs which the status deck may receive to produce a more definitive prediction. The status deck uncertainties should decrease in moving from left to right across the table as more engine cycle and controls constraints are input to the deck. The first column on the left indicates the simplest set of inputs, which require essentially no test measurements and no controls definition. The last column on the right shows complete aircraft/engine interface pressure and temperature measurements and engine power setting as well as full definition of engine controls.

3.2 VALIDATION PROCEDURE

Once a status deck has been constructed and adjusted using sea-level and altitude test results, the deck performance predictions may be validated by comparison to the actual performance of one or more engines. Where several engines have been built, perhaps for a prototype flight test program, an estimate of the engine statistical spread can be computed and the deviation of the status deck from the mean can be noted for individual performance parameters at the various flight conditions. For a sample of one or two engines tested under simulated altitude conditions, whole family comparisons are available only at sea-level static. Any engine family statistical comparisons at altitude are usually inferred from sea-level acceptance data and the testing at altitude of one or more samples. This reasoning is illustrated schematically in Fig. 5, where the status deck bias is determined from altitude test data, and the precision may be inferred from the sea-level acceptance data samples. Bias and precision are then combined to give uncertainty (Ref. 7). Status deck input influence coefficients are also determined, and the method is discussed in Section 4.4.

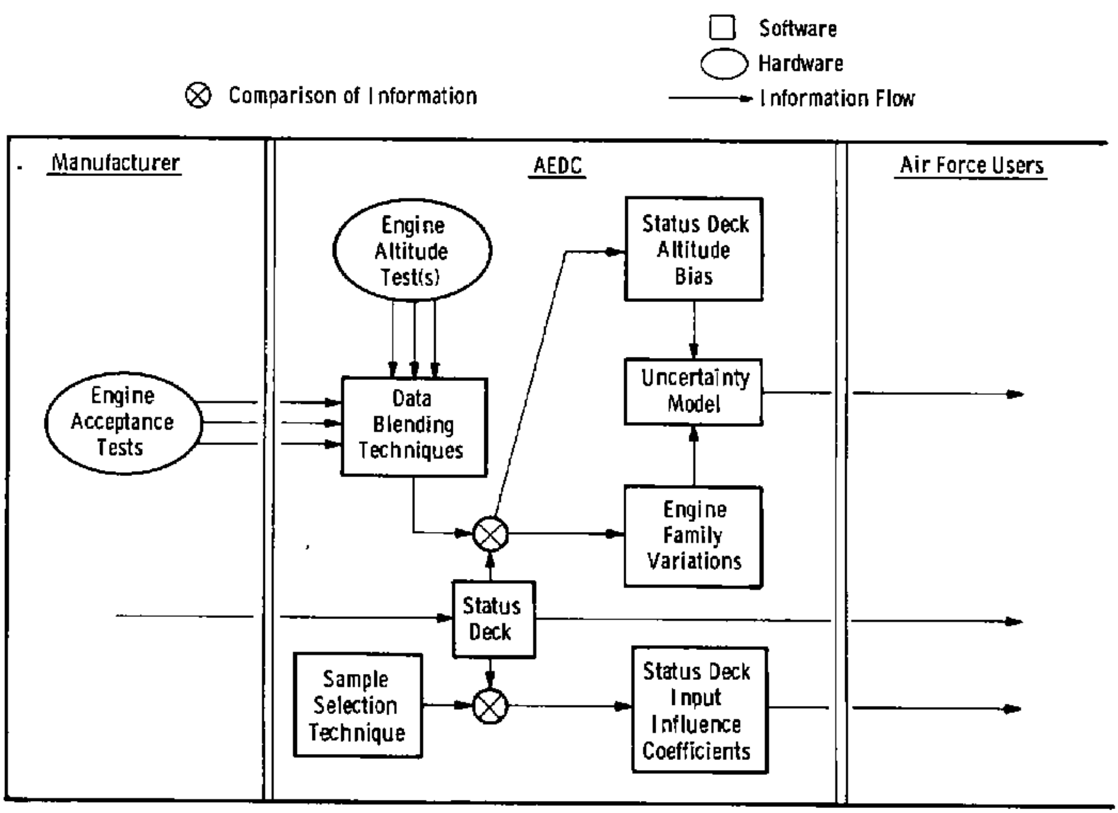


Figure 5. Engine status deck validation at AEDC.

4.0 RESULTS AND DISCUSSION

After the development of a rationale and establishment of a procedure (Section 3.0) for the validation of a turbine engine math model, an example validation is demonstrated and the results are reported herein. The engine and status deck selected for this demonstration are the YJ101-GE-100 and status deck number 74017A, dated August 30, 1974 (Ref. 6). The YJ101-GE-100 engine is a two-spool, augmented turbojet in the 15,000-lbf thrust class and is described in Section 2.1. The YJ101 status deck (No. 74017A) and its input options are described in Section 2.2.3.

The validation of this status deck fits in the next to last engine status category in Fig. 4 (approximately 10 prototype engines with one tested at altitude), as discussed in Section 3.1. One of the engines was tested at simulated altitude conditions at AEDC, and manufacturer sea-level acceptance test data were available on six of the prototype engines. The two engine cycle variables chosen were low pressure compressor speed and turbine exit temperature, since the deck gave more accurate predictions (compared to AEDC test data) using these inputs rather than high pressure compressor speed or exhaust nozzle area, which were also available inputs. All status deck predictions are with MIL-E-5008D ram recovery, zero customer bleed flow, and zero horsepower extraction. Five flight conditions were selected for status deck validation. These five flight conditions were as follows: sea-level static; sea-level, Mach number 0.9; 30,000 ft, Mach number 1.2; 36,000 ft, Mach number 0.8, and 45,000 ft, Mach number 0.9. Engine power settings selected for the validation comparison were part power, intermediate, minimum augmentation, and maximum power.

After selection of the engine and status deck and determination of the category (Fig. 4) of the selection, it must be determined what parameters are of importance and what data measurements are available with which to make comparisons. During past investigations and studies (Ref. 8), it has been shown that turbine engine operational characteristics probably lie in the three following areas, from the military and commercial users' point of view: (1) performance, (2) stability, and (3) durability. Performance is defined in overall terms of thrust (FN) and fuel consumption. Stability is defined in terms of the compressor characteristics of airflow rate (WA) and pressure ratio (PR) observed in various operating environments. Durability is more difficult to characterize, but is normally thought of in terms of mechanical response of the engine parts to the environments in which the parts are operated. For this study durability considerations are characterized by examinations of trends in calculated turbine inlet temperature and high pressure compressor rotor speed (N2).

4.1 STATUS DECK CONTROLS VALIDATION

To begin the status deck validation, controls check curves were generated for the YJ101 control for low compressor speed (Fig. 6), turbine exit temperature (Fig. 7), afterburner fuel flow (Fig. 8), and exhaust nozzle area (Fig. 9). All controlled parameters predicted by the deck were within the manufacturer-prescribed tolerance bands, except for exhaust nozzle area, which agreed well with the test results for engine S/N 214005-1B. Controls verification test data were recorded at several nonstandard temperature conditions in order to generate these check curves.

4.2 ALTITUDE PERFORMANCE VALIDATION

Following the controls verification, the deck was executed at the five flight conditions previously selected for altitude testing, using the four deck input status modes shown in Fig. 4. The percent deviations of the math model predictions from the AEDC test results for engine S/N 214005-1B are tabulated (Table 1) and plotted (Figs. 10 and 11) for three of the operational categories of interest to engine and deck users, as discussed in section 3.2. These categories are performance, stability, and durability. Performance comparisons were made by examination of predicted versus test net thrust (FN) and specific fuel consumption (SFC), stability comparisons were made using engine total airflow rate (WA) and high pressure compressor pressure ratio (PR11), and durability trend comparisons were made using calculated turbine inlet temperature (T4) and high pressure compressor rotor speed (N2). With a few exceptions, the agreement between the status deck predictions and AEDC altitude test data improves as additional, more definitive, status deck inputs were used. Also, agreement was considerably better at the higher engine power settings than at part power. The deviations derived from this portion of the study were averaged by the method of root mean squares (RMS) to be used as bias errors (B) for the uncertainty model (Section 4.4).

It is recognized in making the status deck-to-test result comparisons that the test results have inherent known uncertainty levels associated with them. Therefore, in cases where the status deck bias is no more than the uncertainty of the test parameter of interest, the status deck must be considered to be in perfect agreement with the test result and thus have a zero bias for the purpose of this analysis. It would be necessary to test several engines from the family at simulated altitude conditions to establish the family bias with high confidence.

4.2.1 Performance-Related Parameters

At sea-level static, the net thrust and specific fuel consumption predictions (Table 1a) were within ±2 percent of the AEDC test data at the higher power settings and within ±5 percent at part power. At sea-level, Mach number 0.9, the net thrust deviation ranged

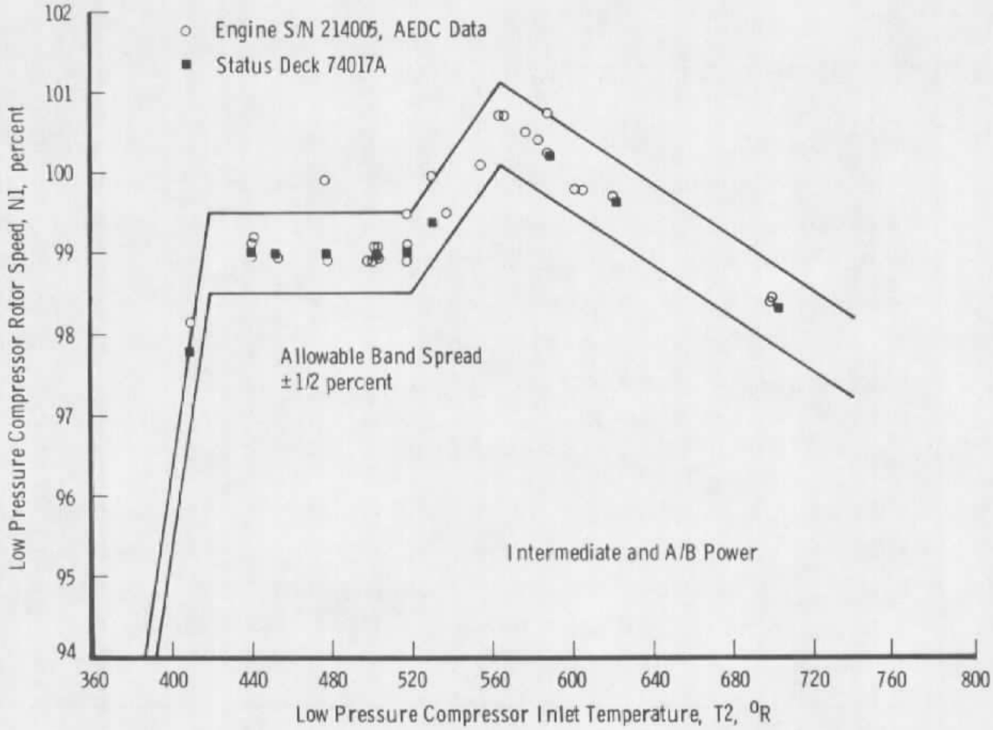


Figure 6. Low pressure compressor rotor speed control trim verification.

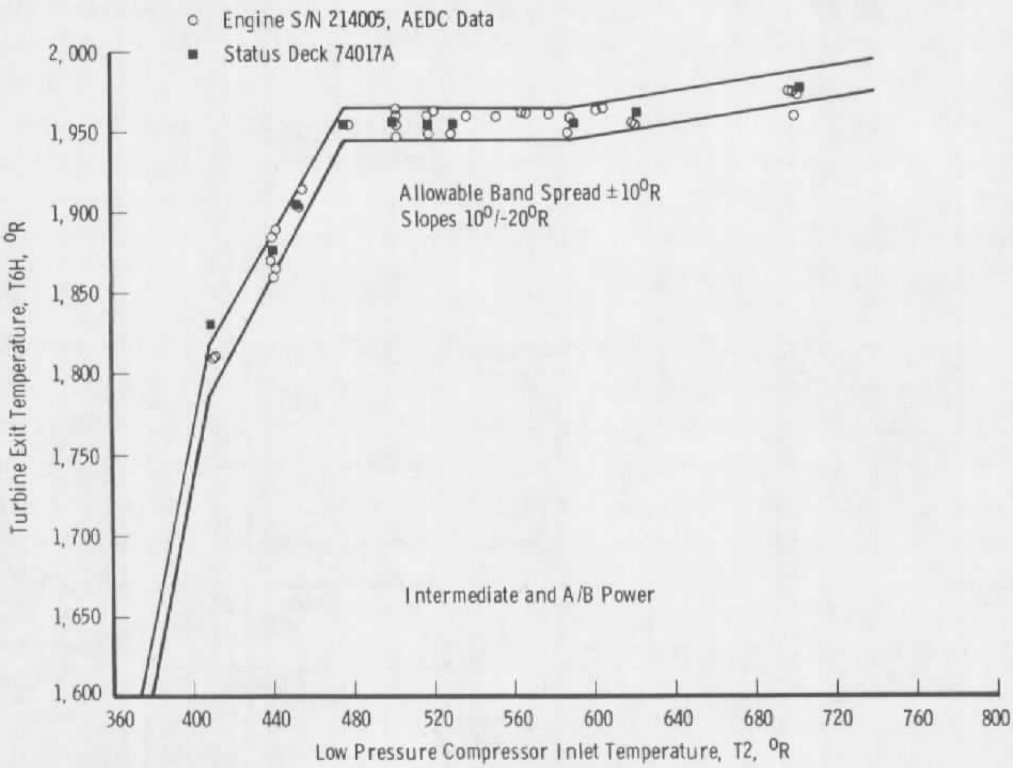


Figure 7. Turbine exit temperature control trim verification.

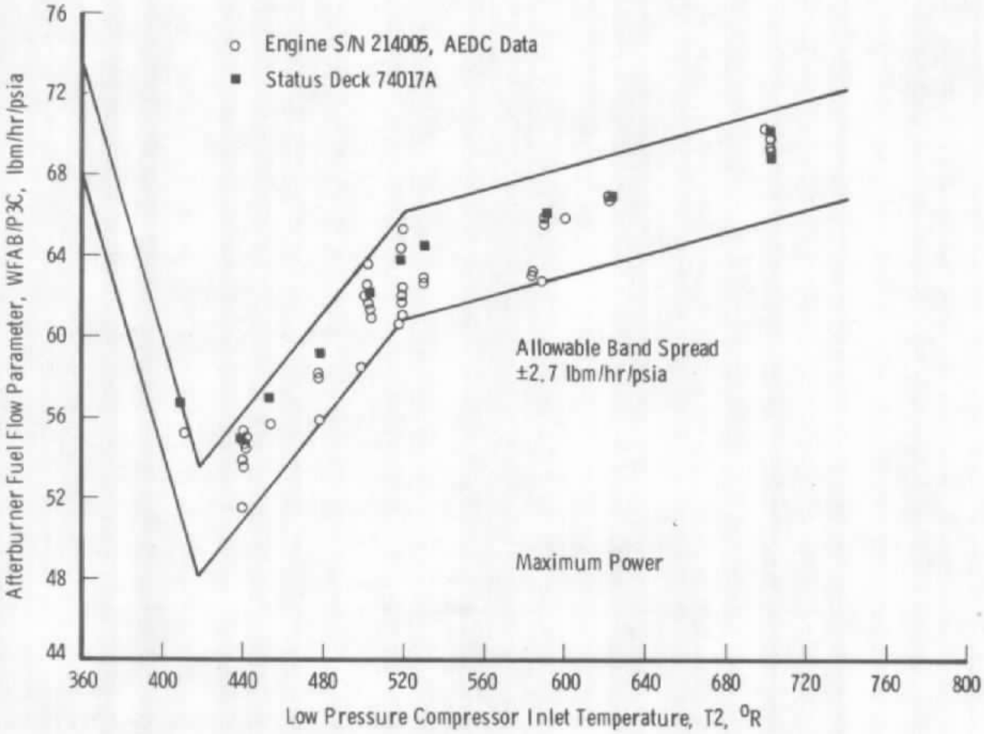


Figure 8. Afterburner fuel flow parameter control trim verification.

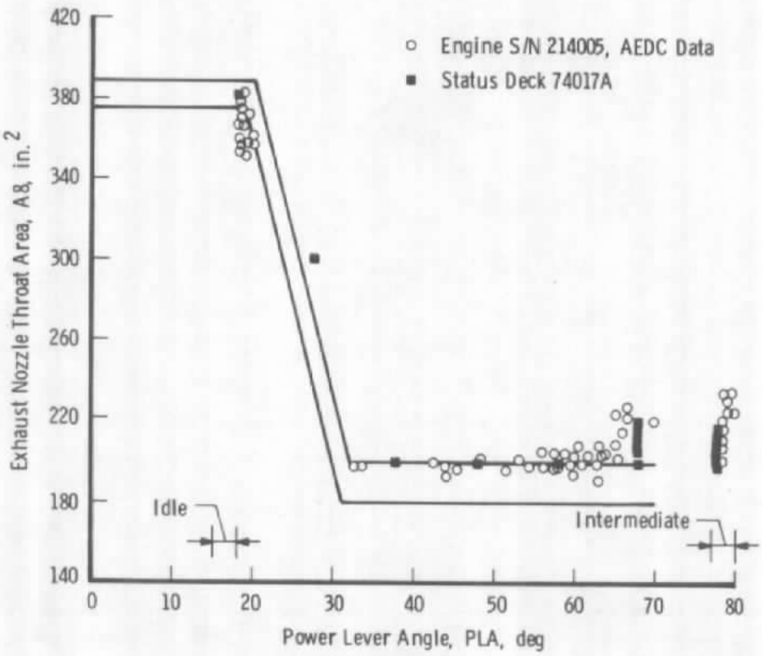
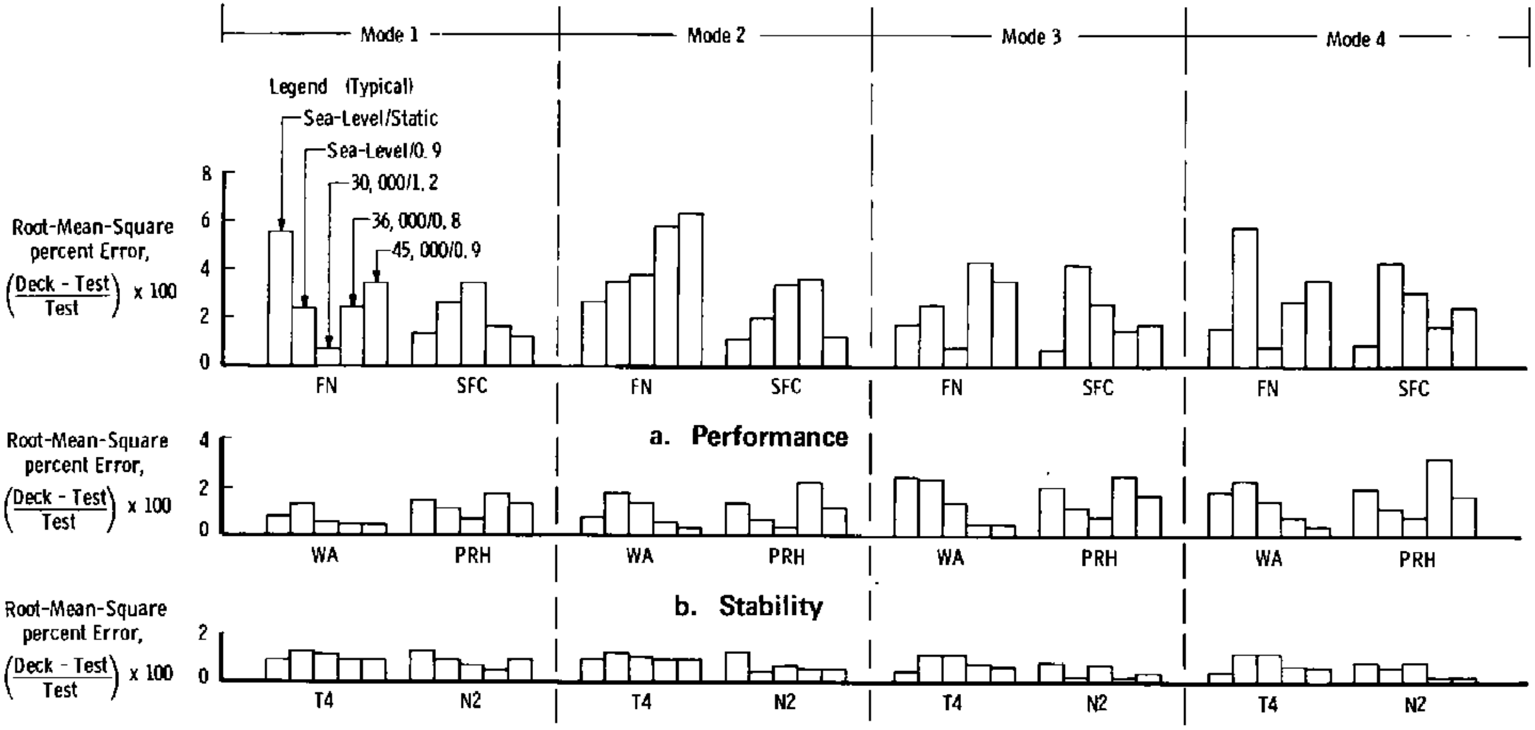


Figure 9. Exhaust nozzle throat area control trim verification.

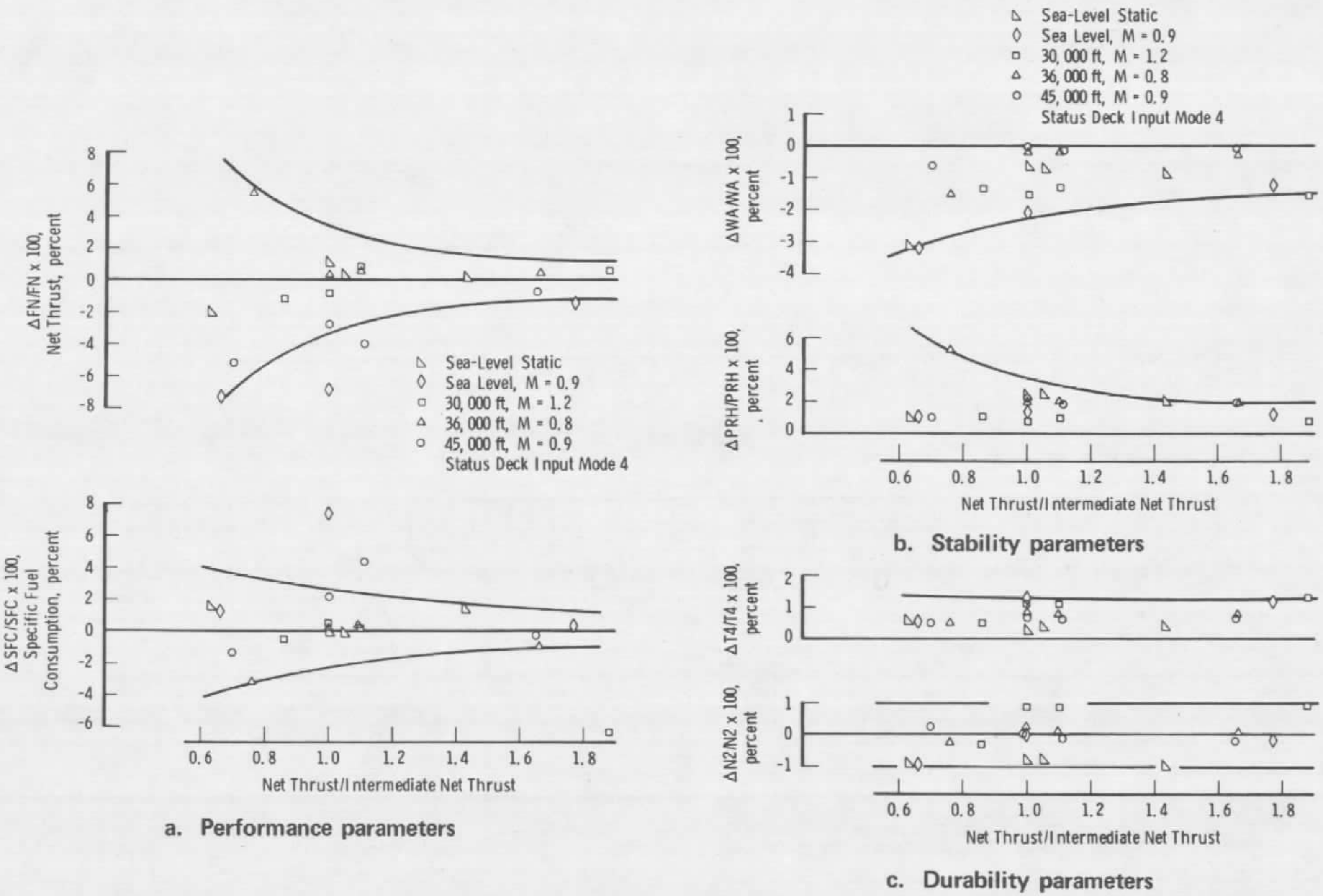


a. Performance

b. Stability

c. Durability

Figure 10. Status deck comparison to AEDC test data at five flight conditions.



a. Performance parameters

b. Stability parameters

c. Durability parameters

Figure 11. Status deck comparison to AEDC altitude test results.

from -7 to 6 percent at part power, and from -7 to 2 percent at the other powers, while the specific fuel consumption deviation was within ±7 percent at all powers. At 30,000 ft, Mach number 1.2, the net thrust deviation varied from -2 to 1 percent, with one exception, while the specific fuel consumption deviation was -7 percent at maximum power and was within ±1 percent at the other powers. At 36,000 ft, Mach number 0.8, the net thrust deviation ranged from -2 to ±10 percent at part power and from -3 to ±1 percent at the other powers, while the specific fuel consumption deviation varied from -7 to -3 percent at part power and was within ±1 percent at the other powers. At 45,000 ft, Mach number 0.9, the net thrust deviation ranged from -5 to 11 percent at part power and ranged from -5 to -1 percent at the other powers, while the specific fuel consumption deviation ranged from -3 to 4 percent for all power settings. A plot of root-mean-square errors for all power settings is presented in Fig. 10a. Status deck performance-related parameter errors generally decrease from mode 1 to mode 4, except at sea level, Mach number 0.9. Plots of these trends versus engine power setting for status deck input mode 4 are presented in Fig. 11a.

4.2.2 Stability-Related Parameters

At sea-level static the engine airflow rate deviation between status deck predictions and test data was approximately -1 percent, with two exceptions at part power of -3 and -5 percent, while high compressor pressure ratio deviation ranged from ±1/2 to ±2-1/2 percent.* At sea level, Mach number 0.9 the engine airflow rate deviation ranged from -1/2 to -3 percent, while the high compressor pressure ratio deviation was within ±1 percent. At 30,000 ft, Mach number 1.2 the engine airflow rate deviation ranged from -1-1/2 to 1/2 percent, while the high compressor pressure ratio deviation ranged from approximately 1/2 to 1-1/2 percent. At 36,000 ft, Mach number 0.9 the engine airflow deviation ranged from 0 to -1-1/2 percent, while the high compressor pressure ratio deviation ranged from 2-1/2 to 5 percent at part power and from 1-1/3 to 2 percent. At 45,000 ft, Mach number 0.9 the engine airflow rate deviation ranged from -1 to 0 percent, while the high compressor pressure ratio deviation ranged from 1/2 to 2-1/4 percent. A plot of root-mean-square errors for all power settings is presented in Fig. 10b. Deck stability-related parameter errors generally increased from mode 1 to mode 4. Plots of these trends versus engine power setting for status deck input mode 4 are presented in Fig. 11b.

4.2.3 Durability-Related Parameters

At sea-level static the calculated turbine inlet temperature deviation between status deck predictions and test data was within ±1/2 percent, with two exceptions of 1-1/2

*Percent values are shown as fractions throughout Sections 4.2.2 and 4.2.3 in order to indicate the approximate nature of these values.

percent at part power, while the high compressor rotor speed deviation ranged from -1-1/4 to -1/3 percent. At sea-level, Mach number 0.9 the turbine inlet temperature deviation ranged from 1/2 to 1-1/2 percent. At 36,000 ft, Mach number 0.8 the deviation ranged from -1/4 to 1 percent, with two exceptions of 1-1/2 percent at part power, while the high compressor rotor speed deviation ranged from -3/4 to 1/4 percent. At 45,000 ft, Mach number 0.9 the turbine inlet temperature deviation was within ±3/4 percent, with two part-power exceptions of 1-1/2 percent, while the high compressor rotor speed deviation ranged from -3/4 to 1/4 percent. A plot of root-mean-square errors for all power settings is shown in Fig. 10c. Deck durability-related parameter errors decrease from mode 1 to mode 4. Plots of these trends versus engine power setting for status deck input mode 4 are presented in Fig. 11c.

4.3 SEA-LEVEL ACCEPTANCE TEST VALIDATION

General Electric sea-level-static acceptance test data for six of the YJ101 engines used in the prototype flight test program were available for comparison with the status deck predictions. There are engine-to-engine variations in the performance-, stability-, and durability-related parameters of any given group of engines; therefore, the statistical spread (±S) was calculated for the six parameters (FN, SFC, WA, PRH, T4, and N2) discussed in the preceding sections and listed in Table 2, at intermediate and maximum power. The net thrust standard deviation was ±0.51 percent at intermediate power and ±0.69 percent at maximum power. The specific fuel consumption standard deviation was ±0.81 percent at intermediate power and ±1.02 percent at maximum power. The engine airflow rate standard deviation was ±1.36 percent, and the high compressor pressure ratio standard deviation was ±0.38 percent at intermediate power. The turbine inlet temperature standard deviation was ±0.13 percent, and the high compressor rotor speed standard deviation was ±0.27 percent at intermediate. The standard deviation was essentially the same at maximum power as at intermediate power for the stability- and durability-related parameters selected for comparison. These values were used as representative of the engine family statistical performance throughout the flight envelope and were employed as indicators of repeatibility or precision errors (S) for the uncertainty model (Section 4.4).

The status deck was executed using the available test inputs (P2, T2, po, to, PLA, N1, and T6) from the acceptance data to make direct comparison with the selected performance-, stability-, and durability-related parameters. Deviations between the predicted and test values were then calculated, and the results are tabulated in Table 3. The average percent deviations for the selected parameters for all six engines are as follows: net thrust = 0.35 (intermediate), net thrust = 0.83 (maximum), specific fuel consumption = -0.72 (intermediate), specific fuel consumption = -2.36 (maximum), engine airflow rate = -0.76, high compressor pressure ratio = -0.23, turbine inlet temperature = 0.62, and high compressor rotor speed = 0.07.

The status deck was then executed using the average inputs from the six acceptance test samples for the mode 4 inputs. These results are tabulated below the average deviations in Table 3. The percent deviations are as follows: net thrust = 0.64 (intermediate) and 1.28 (maximum), specific fuel consumption = -0.93 (intermediate) and -2.36 (maximum), engine airflow rate = -0.80, high compressor pressure ratio = -0.17, turbine inlet temperature = 0.58 and high compressor rotor speed = 0.03. These "average engine" results differed significantly for net thrust and specific fuel consumption values, but only slightly for the other parameters, from the numerical (rms) average value for six engines.

4.4 STATUS DECK UNCERTAINTY MODEL

The validation of the YJ101-GE-100 status deck (No. 74017A) was conducted using AEDC altitude test results for one engine and ground level acceptance test results for six engines. The status deck bias error (B) was developed from the AEDC altitude results at five flight conditions, and the precision(s) was inferred from the engine family spread at sea-level-static condition. Altitude bias errors are tabulated in Table 1 and are discussed in Section 4.2. The five flight condition values were averaged (rms) for four engine power settings to give one value representative of the flight envelope (Table 1f). A few outliers were rejected in computing these averages. These bias errors were then combined with the engine family precision (Table 2) values according to accepted statistical practice (U = ± (B + KS), Ref. 9) where K = 2.571 for six samples, to produce an uncertainty model. The uncertainty model for the YJ101 status deck gives the predicted uncertainties for each parameter of interest, for the four selected status deck input modes, at intermediate and maximum power (Fig. 12) as an example of the application of the validation technique. These uncertainty values are shown superimposed on a previous figure (Fig. 4), where the validation rationale was discussed (Section 3.1). These results show that the intermediate and maximum power values are essentially the same, except for specific fuel consumption, using status deck input modes 1, 2, and 3. The specific results for the three categories of interest are discussed below.

4.4.1 Performance-Related Parameters

The average uncertainty of net thrust for this status deck (74017A, Fig. 12) is ±2.88 percent at intermediate and ±2.60 percent at maximum power using mode 4 inputs. The average uncertainty of specific fuel consumption is ±3.16 percent at intermediate and ±3.46 percent at maximum power using mode 4 inputs. Note that both the net thrust and specific fuel consumption uncertainties generally decrease in moving from mode 1 to mode 4 inputs. Also, specific fuel consumption uncertainty is almost twice as great as the other values for modes 1, 2, and 3 at maximum power.

4.4.2 Stability-Related Parameters

The average uncertainty of engine airflow rate for this status deck (74017A, Fig. 12) is ±4.69 percent at intermediate and ±4.47 percent at maximum power using mode 4 inputs. The average uncertainty of high compressor pressure ratio is ±2.82 percent at intermediate and ±2.56 percent at maximum power using mode 4 inputs. Both airflow rate and high compressor pressure ratio uncertainties increase slightly when moving from mode 1 to mode 4 inputs.

Engine and Data Status \ Status Deck Input Mode		Expected Status Deck Uncertainty, percent							
		1 M, ALT, DAY Engine PLA		2 M, ALT, DAY Engine PLA, N1 or N2		3 M, ALT, to Engine: PLA, N1 or N2, T6 or A8		4 P2, T2, po, to Engine: PLA, N1 or N2, T6 or A8	
Many (1,000) Production Engines Sea-Level Acceptance Data No Altitude Testing									
Many (1,000) Production Engines Sea-Level Acceptance Data Three Tested at Altitude									
Many (1,000) Production Engines Sea-Level Acceptance Data 31 Tested at Altitude									
Several (100) Flight Test Engines Sea-Level Acceptance Data One Tested at Altitude									
Several (100) Flight Test Engines Sea-Level Acceptance Data Five Tested at Altitude									
A Few (10) Prototype Engines Sea-Level Acceptance Data One Tested at Altitude YJ101 Results		Int	Max	Int	Max	Int	Max	Int	Max
	FN	3.63	3.74	3.71	3.53	2.21	3.00	2.88	2.60
	SFC	3.04	6.45	2.98	5.96	2.81	6.80	3.16	3.46
	WA	3.99	3.95	4.68	4.46	4.69	4.47	4.69	4.47
	PRH	2.14	2.07	2.14	2.09	2.82	2.56	2.82	2.56
	T4	1.00	1.04	0.93	0.93	1.25	1.23	1.25	1.23
	N2	1.39	1.46	1.37	1.43	1.22	1.33	1.22	1.33
A Few (10) Prototype Engines Sea-Level Acceptance Data Three Tested at Altitude									
One Development Engine Tested at Altitude									

Figure 12. YJ101 status deck uncertainty.

4.4.3 Durability-Related Parameters

The average uncertainty of turbine inlet temperature for this status deck (74017A, Fig. 12) is ±1.25 percent at intermediate and ±1.23 percent at maximum power using mode 4 inputs. The average uncertainty of high compressor rotor speed is ±1.22 percent at intermediate and ±1.33 percent at maximum power using mode 4 inputs. Turbine inlet temperature uncertainty increases slightly, and high compressor rotor speed uncertainty decreases slightly when moving from mode 1 to mode 4.

4.5 ESTIMATED FLIGHT MEASUREMENT UNCERTAINTY EFFECTS

The status deck input parameters to be measured during flight test, using deck input mode 4 as discussed in the preceding sections. were systematically varied by ±1.0 and ±2.4 percent from the average values according to the rationale developed in Ref. 9. The values of influence coefficients for status deck runs using the deck inputs for mode 4(P2, T2, Po, to, N1, T6, and PLA) are tabulated (Table 4) as a function of flight condition and power setting for the six parameters of interest (FN, SFC, WA. PRH, T4, and N2) to show the expected variations. Altitude ambient temperature and compressor inlet temperature were assumed to vary by the same percentage amount, and compressor inlet pressure and temperature variations were run while holding the low compressor speed, turbine exit temperature, and altitude ambient pressure variations at zero. Likewise, low compressor speed and turbine exit temperature variations were run while the variations of the other inputs were held at zero. The results of this investigation are discussed below.

The derivation of output parameter influence functions to analytically determine the effect on the six selected engine output parameters (FN, SFC, WA, PRH, T4, and N2) of variations in the five independent status deck input parameters (N1, T6, P2, T2, and po, ambient temperature assumed to vary directly with compressor inlet temperature) is discussed below. The technique of Box, et al. as described by Canavos (Ref. 9) was used to derive influence functions. These functions are second-order polynominals of the form $Y = f(X_1, X_1^2, X_iX_j, \text{etc})$, which have minimal errors inside the range of variation (±2.378 percent) for the status deck input parameters. The variation of ±2.378 percent was used for this derivation to insure rotatability of the functions about the entire area of interest as described in Ref. 9. In order to present an overall analytic determination of the variation in output parameters with input parameter variations the engine flight envelope was divided into variations in Mach number (0.0 to 2.0), Reynolds Number Index (0.2 to 1.5), and power lever angle (20 to 130 deg) in order to derive a single equation for each output variable of interest

The Box analysis (Ref. 9) was first used to derive the flight and power conditions of interest within the given ranges. These conditions are shown in Fig. 13. The central point is Mach number 1.0, Reynolds Number Index 0.9 (18,000 ft altitude). The other points are extremes of Mach number or Reynolds Number Index at the central power setting (intermediate), and moderate Mach numbers/Reynolds Number Indices at the moderate power settings (part power, partial A/B). The central flight condition was run at the extreme (low and maximum power) and intermediate power settings.

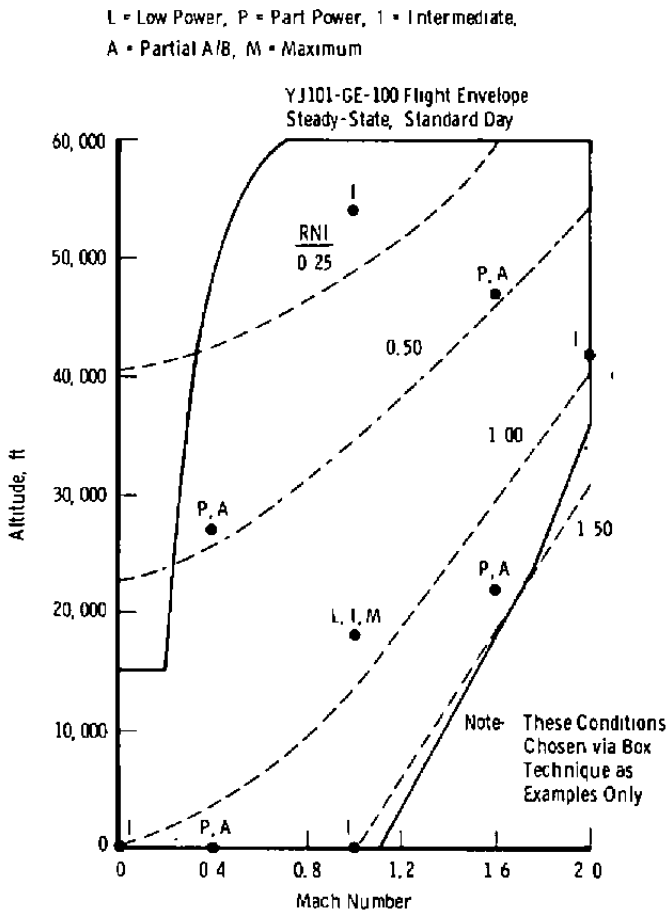


Figure 13. Flight condition and power setting selection for flight prediction uncertainty analysis.

The status deck was then run at these fifteen flight condition/power setting combinations with ±1-percent and ±2.378-percent variations in the five independent input variables (N1, T6, P2, T2, and po) to generate second-order influence functions for the six output parameters (FN, SFC, WA, PRH, T4, and N2). This gave fifteen equations for each parameter to be reduced to one equation by further analysis. This was accomplished by perturbation of the now independent variables (MN, REI, and PLA) by ±1 percent and ±1.682 percent (Ref. 9) to obtain a second Box analysis and give a second-order curve fit for the coefficients of the first set of equations for each of the six output variables as a function of Mach number, Reynolds Number Index, and power lever angle. The variance (VAR) or uncertainty of these curve fits in percent of value was also computed (Ref. 9), and both results are shown in Table 4. The maximum variances of the derived influence function coefficients for this status deck (74017A) are ±0.95 percent for net thrust, ±2.88 percent for specific fuel consumption, ±0.14 percent for engine airflow rate, ±0.03 percent for high compressor pressure ratio, ±0.002 percent for turbine inlet temperature, and ±0.002 percent for high compressor rotor speed.

The use of Table 4 is illustrated by taking a flight condition of 18,000 ft, Mach number 1.0 (RNI = 0.9) at intermediate power (PLA = 78) and determining the effect on net thrust of (for example) a plus one-percent variance in the turbine exit temperature parameter. Since this is the central flight condition and power setting, the top line only of coefficient values in Table 4a would be used, and only those values involving $\Delta T6/T6$ need be considered. Writing the equation gives: $\Delta FN/FN = 0.012 + 2.506 \times \Delta T6/T6 + 0.014 \times (\Delta T6/T6)^2 = 2.532$ percent. The status deck value at this condition from a direct input run is 2.21 percent, thus showing good comparison with the analytic value.

5.0 SUMMARY OF RESULTS

The results of an analysis and evaluation effort to develop a rationale and technique for the validation of turbine engine steady-state mathematical models for use in predicting engine flight test parameters, and a demonstration of the technique, are summarized below:

1. A mathematical model validation rationale and procedure was developed for use with turbine engine steady-state status decks. At the completion of engine development and math model validation an examination and analysis of available flight test inputs can be performed to select the proper inputs to enhance the accuracy of propulsion system performance determinations.

2. The YJ101-GE-100 status deck (No. 74017A) was validated using the developed procedure. Comparisons were made with AEDC altitude test data for one engine and sea-level acceptance test data for six engines.

    a. Status deck bias errors at five flight conditions for one engine ranged to approximately ±6 percent for net thrust and specific fuel consumption, to -3 percent for engine total airflow rate, to 5 percent for high compressor pressure ratio, to 1 percent for turbine inlet temperature, and to ±1 percent for high compressor rotor speed.

b. The six-engine acceptance test precision (S) at sea-level static was ±0.51 percent for net thrust at intermediate power and ±0.69 percent at maximum power, ±0.81 percent for specific fuel consumption at intermediate power and ±1.02 percent at maximum power; precision was ±1.36 percent for airflow rate, ±0.38 percent for high compressor pressure ratio, ±0.13 percent for turbine inlet temperature, and ±0.27 percent for high compressor rotor speed, all at intermediate power and above.

c. Status deck versus acceptance test errors at sea-level static for six engines averaged 0.35 percent for net thrust at intermediate power and 0.83 percent at maximum power, -0.72 percent for specific fuel consumption at intermediate power and -2.36 percent at maximum power; averages were -0.76 percent for airflow rate, -0.23 percent for high compressor pressure ratio, 0.62 percent for turbine inlet temperature, and 0.07 percent for high compressor rotor speed, all at intermediate power and above.

3. An uncertainty model was developed for the YJ101-GE-100 status deck (No. 74017A) using the results developed during altitude test and acceptance test validations. The total uncertainty ±(B + 2.57S) at intermediate and maximum power is ±2.7 percent for net thrust, ±3.3 percent for specific fuel consumption, ±4.6 percent for airflow rate, ±2.7 percent for high compressor pressure ratio, ±1.2 percent for turbine inlet temperature, and ±1.3 percent for high compressor rotor speed.

4. The effects on flight parameter prediction uncertainty of status deck input variations were analytically determined via a newly developed optimization method. This method (Box technique) showed that variations in the independent status deck input parameters from flight test can be analytically determined for any flight conditions by executing the status deck several times and curve-fitting the resultant output parameters of interest.

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Table 1. Math Model Validation, AEDC Test Comparison

$$\text{Percent Error, } \left(\frac{\text{Math Model} - \text{Test}}{\text{Test}}\right) \times 100 \text{ Percent}$$

Engine Category/Power \ Deck Input Mode	1 M, ALT, DAY Engine: PLA		2 M, ALT, to Engine: PLA, N1		3 M, ALT, to Engine: PLA, N1, T6		4 P2, T2, po, to Engine: PLA, N1, T6	
a. Sea-Level/Static								
Performance	FN	SFC	FN	SFC	FN	SFC	FN	SFC
Part Power	-5.00	-1.58	5.17*	0.24	-2.68	-0.61	-2.04	1.48
Intermediate	-1.68	-1.18	-1.16	-1.17	1.67	-0.59	1.07	-0.05
Minimum Augmentation	-1.19	1.31	-0.99	-1.29	1.77	-0.85	0.18	-0.12
Maximum	-9.50*	1.40	-1.02	1.22	0.71	0.64	0.13	1.29
Stability	WA	PRH	WA	PRH	WA	PRH	WA	PRH
Part Power	-0.96	1.41	-1.08	0.47	-4.71	0.75	-3.16	0.96
Intermediate	-0.77	1.35	-0.61	1.50	-0.64	2.37	-0.64	2.37
Minimum Augmentation	-0.70	1.47	-0.70	1.53	-0.73	2.39	-0.73	2.39
Maximum	-0.73	1.50	-0.87	1.54	-0.87	1.93	-0.87	1.93
Durability	T4	N2	T4	N2	T4	N2	T4	N2
Part Power	1.60	-1.18	1.57	-0.56	0.52	-0.34	0.52	-0.95
Intermediate	-0.58	-1.24	-0.62	-1.29	0.28	-0.79	0.28	-0.78
Minimum Augmentation	-0.48	-1.22	-0.52	-1.26	0.34	-0.77	0.34	-0.77
Maximum	-0.01	-1.26	-0.03	-1.29	0.35	-1.08	0.35	-1.08
b. Sea-Level/M = 0.9								
Performance	FN	SFC	FN	SFC	FN	SFC	FN	SFC
Part Power	-3.78	-0.17	5.98*	-1.89	3.81	-1.59	-7.35	1.23
Intermediate	1.13	-0.86	-1.02	-0.65	0.70	-1.29	-6.89*	7.35*
Maximum	1.04	-4.70	0.83	-2.81	2.08	-6.87	-1.45	0.24
Stability	WA	PRH	WA	PRH	WA	PRH	WA	PRH
Part Power	-2.01	1.41	-2.22	0.47	-3.20	0.75	-3.16	0.96
Intermediate	-0.70	0.99	-2.02	0.58	-2.04	1.34	-2.04	1.34
Maximum	-0.58	0.77	-1.18	0.77	-1.19	1.15	-1.19	1.15
Durability	T4	N2	T4	N2	T4	N2	T4	N2
Part Power	1.60	-1.54	1.57	-0.47	0.52	-0.28	0.52	-0.95
Intermediate	0.87	-0.19	0.80	-0.19	1.28	0.02	1.28	0.02
Maximum	0.97	-0.16	0.87	-0.25	1.15	-0.13	1.15	-0.13

*Value considered to be an outlier and excluded from average (Table 1f)

Table 1. Continued

Percent Error, $\left(\frac{\text{Math Model} - \text{Test}}{\text{Test}}\right) \times$ 100 Percent

Engine Category/Power \ Deck Input Mode	1 M, ALT, DAY Engine: PLA		2 M, ALT, to Engine: PLA, N1		3 M, ALT, to Engine: PLA, N1, T6		4 P2, T2, po, to Engine: PLA, N1, T6	
c. 30,000 ft/M = 1.2								
Performance	FN	SFC	FN	SFC	FN	SFC	FN	SFC
Part Power	-1.21	-0.80	7.36	1.22	-1.22	-0.27	-1.20	-0.53
Intermediate	-0.23	-0.44	-2.09	-0.20	-0.52	0.18	-0.89	0.48
Minimum Augmentation	0.48	-0.55	-1.08	-0.28	-0.49	0.19	0.67	0.11
Maximum	0.71	-6.73	-0.88	-6.52	0.38	-5.33	0.59	-6.16*
Stability	WA	PRH	WA	PRH	WA	PRH	WA	PRH
Part Power	-0.91	1.41	-0.87	0.47	-0.85	0.75	-1.37	0.96
Intermediate	0.33	0.27	-1.56	0.18	-1.56	0.70	-1.56	0.70
Minimum Augmentation	0.41	0.35	-1.37	0.23	-1.37	0.88	-1.37	0.88
Maximum	0.30	0.35	-1.54	0.16	-1.56	0.71	-1.56	0.71
Durability	T4	N2	T4	N2	T4	N2	T4	N2
Part Power	1.60	-0.77	1.57	-0.77	0.52	0.22	0.52	-0.31
Intermediate	0.87	0.74	0.63	0.55	1.15	0.86	1.15	0.86
Minimum Augumentation	0.80	0.78	0.56	0.58	1.11	0.89	1.11	0.91
Maximum	1.01	0.81	0.77	0.62	1.29	0.91	1.29	0.91
d. 36,000 ft/M = 0.8								
Performance	FN	SFC	FN	SFC	FN	SFC	FN	SFC
Part Power	-2.17	-3.16	10.90*	-6.96	8.51	-2.27	5.38	-3.26
Intermediate	-2.54	-0.86	-2.51	-0.87	0.56	-0.29	0.30	0.07
Minimum Augmentation	-2.32	-0.30	-2.32	-0.29	0.75	-0.06	0.49	0.35
Maximum	-2.77	-0.66	-2.69	-0.69	0.54	-0.10	0.36	-1.01
Stability	WA	PRH	WA	PRH	WA	PRH	WA	PRH
Part Power	-0.86	2.68	-0.85	3.65	-0.85	3.63	-1.51	5.11*
Intermediate	-0.12	1.33	-0.14	1.40	-0.16	1.99	-0.16	1.99
Minimum Augmentation	-0.11	1.33	-0.13	1.33	-0.15	1.99	-0.15	1.99
Maximum	-0.12	1.33	-0.26	1.33	-0.28	1.86	-0.28	1.86
Durability	T4	N2	T4	N2	T4	N2	T4	N2
Part Power	1.60	-0.61	1.57	-0.77	0.52	0.22	0.52	-0.23
Intermediate	-0.25	-0.27	-0.29	-0.28	0.82	0.19	0.82	0.19
Minimum Augmentation	-0.25	-0.37	-0.25	-0.35	0.82	0.12	0.82	0.12
Maximum	-0.25	-0.37	-0.25	-0.36	0.78	0.09	0.78	0.09

*Value considered to be an outlier and excluded from average (Table 1f)

Table 1. Concluded

$$\text{Percent Error, } \left(\frac{\text{Math Model} - \text{Test}}{\text{Test}}\right) \times 100 \text{ Percent}$$

Engine Category/Power \ Deck Input Mode	1 M, ALT, DAY Engine: PLA		2 M, ALT, to Engine: PLA, N1		3 M, ALT, to Engine: PLA, N1, T6		4 P2, T2, po, to Engine: PLA, N1, T6	
	e. 45,000 ft/M = 0.9							
Performance	FN	SFC	FN	SFC	FN	SFC	FN	SFC
Part Power	-1.94	-0.96	10.90*	-0.19	6.78	-1.26	-5.17	-1.40
Intermediate	-4.03	-1.25	-3.98	-1.21	-0.38	-0.75	-2.79	2.11
Minimum Augmentation	-4.78	1.01	-4.78	1.04	-1.12	0.81	-4.02*	4.36*
Maximum	-2.49	-1.90	-2.38	-1.85	1.52	-3.35	-0.92	-0.22
Stability	WA	PRH	WA	PRH	WA	PRH	WA	PRH
Part Power	-0.86	1.41	-0.65	0.47	-0.83	0.75	-0.65	0.96
Intermediate	-0.02	1.46	-0.08	1.45	-0.08	2.24	-0.08	2.24
Minimum Augmentation	-0.08	1.02	-0.15	0.99	-0.15	1.77	-0.15	1.77
Maximum	-0.15	1.11	-0.08	1.07	-0.07	1.85	-0.07	1.85
Durability	T4	N2	T4	N2	T4	N2	T4	N2
Part Power	1.60	-0.67	1.57	0.17	0.52	-0.63	0.52	0.23
Intermediate	-0.56	-0.50	-0.56	-0.50	0.70	0.06	0.70	0.06
Minimum Augmentation	-0.63	-0.69	-0.60	-0.65	0.67	-0.10	0.67	-0.10
Maximum	-0.70	-0.76	-0.63	-0.72	0.60	-0.18	0.60	-0.18
	f. Average (Root Sum Square)							
Performance	FN	SFC	FN	SFC	FN	SFC	FN	SFC
Part Power	3.14	1.68	8.42*	1.14	5.32	1.39	4.80	1.82
Intermediate	2.32	0.96	2.40	0.90	0.90	0.73	1.57	1.08
Minimum Augmentation	2.73	0.88	2.76	0.85	1.14	0.60	0.49	0.22
Maximum	1.97	3.83	1.76	3.34	1.23	4.18	0.83	0.84
Average	2.57	2.24	2.31	1.91	2.89	2.31	9.64	1.17
Stability	WA	PRH	WA	PRH	WA	PRH	WA	PRH
Part Power	1.21	1.74	1.26	0.47	2.63	0.75	2.22	0.96
Intermediate	0.49	1.16	1.18	1.16	1.19	1.84	1.19	1.84
Minimum Augmentation	0.41	1.13	0.78	1.13	0.78	1.84	0.78	1.84
Maximum	0.45	1.09	0.96	1.09	0.97	1.58	0.97	1.58
Average	0.73	1.32	1.07	1.00	1.60	1.55	1.43	1.58
Durability	T4	N2	T4	N2	T4	N2	T4	N2
Part Power	1.60	1.02	1.57	0.59	0.52	0.37	0.52	0.63
Intermediate	0.67	0.70	0.60	0.68	0.92	0.53	0.92	0.53
Minimum Augmentation	0.58	0.82	0.50	0.79	0.79	0.59	0.79	0.59
Maximum	0.71	0.77	0.60	0.74	0.90	0.64	0.90	0.64
Average	1.00	0.84	0.94	0.70	0.80	0.54	0.80	0.60

*Value considered to be an outlier and excluded from average

Table 2. Acceptance Test Data Spread

Engine Serial Number	Percent of Average Value			
	a. Performance			
	$\Delta FN/FN_{AVG}$		$\Delta SFC/SFC_{AVG}$	
	Intermediate	Maximum	Intermediate	Maximum
214005-2B	0.33	-1.02	0.06	0.10
214101-2B	0.90	0.92	-0.76	-1.11
214102-1C	0.03	0.80	-0.88	-0.82
214103-1B	-0.43	-0.16	1.23	2.07
214104-1B	-0.20	0.04	0.88	0.05
214105-1B	-0.62	-0.58	-0.53	-0.24
±1 Standard Deviation, percent	0.51	0.69	0.81	1.02

Engine Serial Number	b. Stability, Intermediate Power	
	$\Delta WA/WA_{AVG}$	$\Delta PRH/PRH_{AVG}$
214005-2B	-2.73	0.34
214101-2B	-0.56	-0.34
214102-1C	0.88	1.00
214103-1B	1.44	0.68
214104-1B	0.64	-0.34
214105-1B	0.16	-0.17
±1 Standard Deviation, percent	1.36	0.38

Engine Serial Number	c. Durability, Intermediate Power	
	$\Delta T4/T4_{AVG}$	$\Delta N2/N2_{AVG}$
214005-2B	0.13	-0.47
214101-2B	-0.11	0.21
214102-1C	-0.15	0.02
214103-1B	0.20	0.02
214104-1B	0.06	-0.04
214105-1B	-0.11	0.27
±1 Standard Deviation, percent	0.13	0.27

Table 3. Math Model Validation, Acceptance Test Comparison and Significance

$$\text{Percent Error}, \left(\frac{\text{Math Model} - \text{Test}}{\text{Test}}\right) \times 100 \text{ Percent}$$

a. Performance

Engine Serial Number	FN		SFC	
	Intermediate	Maximum	Intermediate	Maximum
214005-2B	-1.86	-3.82	-1.53	-1.98
214101-2B	-0.31	-0.22	-2.10	-3.90
214102-1C	2.37	3.71	-1.16	-3.82
214103-1B	0.81	-0.02	1.55	1.43
214104-1B	0.04	1.00	0.00	-3.32
214105-1B	1.05	0.53	-1.05	-2.55
Average	0.35	0.83	-0.72	-2.36
Average Engine	0.64	1.28	-0.93	-3.32

b. Stability, Intermediate Power

Engine Serial Number	WA	PRH
214005-2B	-2.03	-0.69
214101-2B	-0.40	-1.02
214102-1C	0.32	0.17
214103-1B	-1.06	0.69
214104-1B	0.08	-0.68
214105-1B	2.33	0.17
Average	-0.76	-0.23
Average Engine	-0.80	-0.17

c. Durability, Intermediate Power

Engine Serial Number	T4	N2
214005-2B	-0.21	-0.92
214101-2B	-0.14	-0.09
214103-1C	1.00	0.35
214103-1B	1.24	0.24
214104-1B	0.52	-0.10
214105-1B	1.34	0.94
Average	0.62	0.07
Average Engine	0.58	0.03

*Deck Input Mode 4 (PLA, N1, T6, P2, T2, po, to)

Table 4. Influence Coefficients for Status Deck Input Variations

Introduction — Table Use

1. The desired output parameter is located as follows:

   Table 4a. Performance: Net Thrust

   4b. Performance: Specific Fuel Consumption

   4c. Stability: Engine Airflow Rate

   4d. Stability: High Compressor Pressure Ratio

   4e. Durability: Turbine Inlet Temperature

   4f. Durability: High Compressor Rotor Speed

2. The desired flight condition is referenced to the central point condition (Mach number 1.0, Reynolds number index 0.9, PLA=78 deg) to get ΔMN/MN, ΔRNI/RNI, and ΔPLA/PLA, all in percent.

3. The errors for the status deck input parameter being investigated are determined in percent (ΔN1/N1, ΔT6/T6, ΔP2/P2, ΔT2/T2, Δpo/po).

4. The coefficients for the net thrust equation, for example, are then determined for those input parameter terms which apply, for example: $C_1 = 1.445 + 0.362\ \Delta MN/MN + 0.332\ \Delta RNI/RNI + 0.306\ \Delta PLA/PLA + 0.227\ (\Delta MN/MN)^2 - 0.178\ (\Delta RNI/RNI)^2 - 1.131\ (\Delta PLA/PLA)^2 - 0.311\ (\Delta MN/MN) \times (\Delta RNI/RNI) + 0.254\ (\Delta MN/MN) \times (\Delta PLA/PLA) + 0.197\ (\Delta RNI/RNI) \times (\Delta PLA/PLA)$ (Table 4a). The other coefficients are likewise computed for the other applicable status deck input terms.

5. For example, the equation for the percent change in net thrust with change in the status deck input parameters is then written as follows: $\Delta FN/FN = C_0 + C_1\ \Delta N1/N1 = C_2\ \Delta T6/T6 + C_3\ \Delta P2/P2 + C_4\ \Delta T2/T2 + C_5\ \Delta po/po + C_6\ (\Delta N1/N1)^2 + C_7\ (\Delta T6/T6)^2 + C_8\ (\Delta P2/P2)^2 + C_9\ (\Delta T2/T2)^2 + C_{10}\ (\Delta po/po)^2 + C_{11}\ (\Delta N1/N1) \times (\Delta T6/T6) + C_{12}\ (\Delta N1/N1) \times (\Delta P2/P2) + C_{13}\ (\Delta N1/N1) \times (\Delta T2/T2) + C_{14}\ (\Delta N1/N1) \times (\Delta po/po) + C_{15}\ (\Delta T6/T6) \times (\Delta P2/P2) + C_{16}\ (\Delta T6/T6) \times (\Delta T2/T2) + C_{17}\ (\Delta T6/T6) \times (\Delta po/po) + C_{18}\ (\Delta P2/P2) \times (\Delta T2/T2) + C_{19}\ (\Delta P2/P2) \times (\Delta po/po) + C_{20}\ (\Delta T2/T2) \times (\Delta po/po)$, percent.

Table 4. Continued
a. Performance: Net Thrust
ΔFN/FN = f(ΔN1/N1, ΔT6/T6, ΔP2/P2, ΔT2/T2, Δpo/po), percent

	C_i = f(ΔMN/MN, ΔRNI/RNI, ΔPLA/PLA), percent																				
	C_0 +	C_1 +	C_2 +	C_3 +	C_4 +	C_5 +	C_6 +	C_7 +	C_8 +	C_9 +	C_{10} +	C_{11} +	C_{12} +	C_{13} +	C_{14} +	C_{15} +	C_{16} +	C_{17} +	C_{18} +	C_{19} +	C_{20}
Flight Cond. / Power	0 012	1 445	2 506	1 326	-2 488	-0 339	-0 080	0 014	0.010	0 045	0.012	0.020	0 028	-0 004	-0 011	0 006	-0 050	0 019	-0 015	0 002	-0 006
ΔMN*/MN	-0.023	0 362	-0.418	-0 164	0 029	0.162	0 040	-0 025	0.031	-0 009	-0 009	-0 045	0 030	-0 052	-0 027	0 025	0 012	-0.039	-0 025	0 031	0 018
ΔRNI*/RNI	-0 011	0 332	0 141	0 055	-0 198	-0.153	-0.074	-0.048	-0 022	-0.053	0 004	-0 051	-0.004	0 101	-0.021	-0.006	0.078	-0.016	0.009	0.022	0 024
ΔPLA*/PLA	-0.018	0.306	-1.314	-0.592	1.339	0 760	-0.103	0 060	-0.004	0.029	0 019	0 002	-0.048	0.081	0 027	0.059	-0.179	-0.044	-0.007	-0.025	0 043
(ΔMN/MN)^2	-0.012	0.227	-0.373	-0.013	0.100	0 107	0.019	0.038	-0.009	0 008	-0.018	-0.031	0.014	0.044	-0.002	0.030	-0.044	-0.037	-0.045	0.000	0.022
(ΔRNI/RNI)^2	-0.013	-0.178	-0.340	-0.013	0.192	0.071	-0.007	0.001	-0.019	-0.050	-0.017	-0.105	-0.032	0.113	0.000	0.003	0.035	-0.032	0.016	-0 002	0 023
(ΔPLA/PLA)^2	-0.004	-1.131	1 577	0.486	-1.183	-0.720	-0.066	-0 210	-0.022	-0.057	-0.030	0.228	0.013	-0.137	-0.036	-0 051	0.198	0.088	0.046	0.035	-0.044
ΔMN/MN ΔRNI/RNI	-0.019	-0.311	-0.522	-0.165	0 397	0.170	0.020	-0 036	-0.030	-0.031	-0 058	-0 060	0.052	0.005	-0.043	0 049	0.039	-0 063	-0 039	0.045	0.037
ΔMN/MN ΔPLA/PLA	-0.027	0 254	0 054	0.125	-0.360	-0.116	-0.009	-0.037	-0.029	-0.027	-0.064	0 052	-0.055	-0.072	0.047	-0.051	-0.029	0.059	0.039	-0 047	-0 033
ΔRNI/RNI ΔPLA/PLA	-0.005	0.197	-0.220	-0.164	0.103	0.199	-0 037	0 005	-0 008	0.006	-0.035	0.018	-0.039	-0.034	0.034	-0 025	-0 060	0.029	0 047	-0 034	-0 041
Status Deck Inputs	1	ΔN1/N1	ΔT6/T6	ΔP2/P2	ΔT2/T2	Δpo/po	(ΔN1/N1)^2	(ΔT6/T6)^2	(ΔP2/P2)^2	(ΔT2/T2)^2	(Δpo/po)^2	ΔN1/N1 x ΔT6/T6	ΔN1/N1 x ΔP2/P2	ΔN1/N1 x ΔT2/T2	ΔN1/N1 x Δpo/po	ΔT6/T6 x ΔP2/P2	ΔT6/T6 x ΔT2/T2	ΔT6/T6 x Δpo/po	ΔP2/P2 x ΔT2/T2	ΔP2/P2 x Δpo/po	ΔT2/T2 x Δpo/po
VAR, ± percent	0.001	0 950	0.851	0.047	0 316	0.173	0.011	0 014	0.002	0 012	0.001	0.008	0.005	0.015	0.001	0.014	0 025	0 011	0.015	0 001	0 010

*Variation from M = 1, RNI = 0 9, PLA = 78

Table 4. Continued
b. Performance: Specific Fuel Consumption
ΔSFC/SFC = f(ΔN1/N1, ΔT6/T6, ΔP2/P2, ΔT2/T2, Δpo/po), percent

	C_i = f(ΔMN/MN, ΔRNI/RNI, ΔPLA/PLA), percent																				
	C_0 +	C_1 +	C_2 +	C_3 +	C_4 +	C_5 +	C_6 +	C_7 +	C_8 +	C_9 +	C_{10} +	C_{11} +	C_{12} +	C_{13} +	C_{14} +	C_{15} +	C_{16} +	C_{17} +	C_{18} +	C_{19} +	C_{20}
Flight Cond / Power	-0.004	-0.006	0.088	-0.344	0.431	0.341	0.070	0.060	-0.003	-0.004	-0.006	-0.080	-0.011	0.015	0.010	0.017	-0.037	-0.018	-0.007	-0.008	0.006
$\frac{\Delta MN}{MN}$*	0.000	-0.174	0.276	0.201	-0.142	-0.194	-0.033	-0.026	-0.016	-0.018	-0.005	0.040	0.003	0.020	-0.004	-0.020	0.034	0.020	0.029	0.010	0.018
$\frac{\Delta RNI}{RNI}$*	0.000	-0.047	-0.216	-0.111	0.184	0.132	0.013	0.019	0.016	0.014	0.003	0.001	0.000	-0.013	0.000	0.073	-0.025	-0.020	-0.008	-0.010	0.018
$\frac{\Delta PLA}{PLA}$*	-0.005	-0.613	2.151	0.843	-1.858	-0.809	-0.079	-0.011	-0.018	0.062	0.000	0.182	0.028	-0.050	-0.029	-0.003	-0.078	0.003	0.001	0.038	-0.012
$\left(\frac{\Delta MN}{MN}\right)^2$	0.000	-0.121	0.397	0.113	-0.324	-0.115	0.033	0.050	0.010	0.038	0.005	-0.050	0.009	-0.022	-0.009	0.008	-0.050	-0.010	-0.018	0.005	0.012
$\left(\frac{\Delta RNI}{RNI}\right)^2$	0.001	0.052	0.219	0.066	-0.242	-0.081	0.074	0.061	0.011	0.043	0.007	-0.055	0.008	0.005	-0.007	0.020	-0.071	-0.014	-0.022	0.004	0.015
$\left(\frac{\Delta PLA}{PLA}\right)^2$	0.004	0.449	-2.178	-0.793	1.904	0.756	-0.134	-0.183	0.004	-0.088	-0.005	0.218	-0.030	0.019	0.030	-0.012	0.142	0.011	0.001	-0.034	-0.003
$\frac{\Delta MN}{MN}\frac{\Delta RNI}{RNI}$	0.006	-0.006	0.450	0.222	-0.343	-0.191	-0.017	-0.022	0.020	-0.009	0.002	0.016	-0.001	0.023	-0.003	-0.030	0.038	0.031	0.011	0.017	-0.030
$\frac{\Delta MN}{MN}\frac{\Delta PLA}{PLA}$	-0.002	-0.068	-0.122	-0.184	0.230	0.176	-0.013	0.015	0.026	0.011	0.006	0.018	0.002	0.003	-0.001	0.023	-0.033	-0.025	-0.007	-0.014	0.027
$\frac{\Delta RNI}{RNI}\frac{\Delta PLA}{PLA}$	0.003	-0.044	0.238	0.162	-0.239	-0.161	0.028	0.023	-0.023	-0.019	-0.002	0.012	0.003	-0.025	-0.002	-0.028	0.050	0.027	0.052	0.016	-0.028
Status Deck Inputs	1	$\frac{\Delta N1}{N1}$	$\frac{\Delta T6}{T6}$	$\frac{\Delta P2}{P2}$	$\frac{\Delta T2}{T2}$	$\frac{\Delta po}{po}$	$\left(\frac{\Delta N1}{N1}\right)^2$	$\left(\frac{\Delta T6}{T6}\right)^2$	$\left(\frac{\Delta P2}{P2}\right)^2$	$\left(\frac{\Delta T2}{T2}\right)^2$	$\left(\frac{\Delta po}{po}\right)^2$	ΔN1/N1 x ΔT6/T6	ΔN1/N1 x ΔP2/P2	ΔN1/N1 x ΔT2/T2	ΔN1/N1 x Δpo/po	ΔT6/T6 x ΔP2/P2	ΔT6/T6 x ΔT2/T2	ΔT6/T6 x Δpo/po	ΔP2/P2 x ΔT2/T2	ΔP2/P2 x Δpo/po	ΔT2/T2 x Δpo/po
VAR, ± percent	0.000	0.485	2.88	0.223	1.51	0.219	0.014	0.011	0.001	0.012	0.000	0.045	0.001	0.002	0.001	0.002	0.032	0.002	0.003	0.000	0.002

*Variation from M = 1, RNI = 0.9, PLA = 78

Table 4. Continued
c. Stability: Engine Airflow Rate
ΔWA/WA = f(ΔN1/N1, ΔT6/T6, ΔP2/P2, ΔT2/T2, Δpo/po), percent

	C_i = f(ΔMN/MN, ΔRNI/RNI, ΔPLA/PLA), percent																				
	C_0 +	C_1 +	C_2 +	C_3 +	C_4 +	C_5 +	C_6 +	C_7 +	C_8 +	C_9 +	C_{10} +	C_{11} +	C_{12} +	C_{13} +	C_{14} +	C_{15} +	C_{16} +	C_{17} +	C_{18} +	C_{19} +	C_{20}
Flight Cond / Power	-0.010	1.90	-0.002	1.03	-1.31	0.0007	-0.093	-0.012	-0.091	-0.013	-0.013	-0.003	0.041	-0.039	0.0007	-0.001	0.003	-0.00009	-0.178	-0.0007	-0.0007
$\frac{\Delta MN^*}{MN}$	-0.022	0.025	0.006	-0.002	-0.114	0.021	0.004	-0.026	-0.026	-0.018	-0.064	0.007	-0.004	-0.019	-0.002	-0.002	0.0006	-0.003	-0.005	0.002	-0.002
$\frac{\Delta RNI^*}{RNI}$	-0.004	0.220	-0.078	-0.060	-0.066	0.022	-0.047	-0.045	-0.016	-0.052	-0.040	-0.056	-0.037	0.080	-0.0003	-0.022	0.068	-0.00002	0.046	0.00003	0.000006
$\frac{\Delta PLA^*}{PLA}$	-0.023	-0.014	-0.018	-0.008	-0.072	0.022	-0.045	-0.025	-0.028	-0.028	-0.061	-0.004	0.002	0.021	-0.0003	0.002	-0.002	-0.0006	-0.001	-0.0003	-0.0004
$\left(\frac{\Delta MN}{MN}\right)^2$	-0.00[illegible]	-0.012	0.007	0.002	-0.006	-0.009	0.042	-0.001	0.023	0.025	0.006	0.022	0.003	-0.036	-0.003	0.004	-0.014	-0.003	0.040	0.002	-0.003
$\left(\frac{\Delta RNI}{RNI}\right)^2$	-0.008	-0.303	-0.112	-0.070	0.226	-0.007	-0.037	-0.036	0.006	-0.064	0.005	-0.060	-0.055	0.121	0.0004	-0.024	0.075	0.0008	0.113	-0.0008	0.0005
$\left(\frac{\Delta PLA}{PLA}\right)^2$	-0.008	-0.188	0.051	0.009	0.034	-0.007	0.027	-0.004	0.022	0.006	0.002	0.017	-0.002	-0.015	-0.0009	0.005	-0.021	0.001	0.043	0.0001	0.001
$\frac{\Delta MN}{MN}\frac{\Delta RNI}{RNI}$	-0.023	-0.283	-0.0005	-0.001	0.098	-0.038	-0.008	-0.026	-0.028	-0.024	0.035	0.002	-0.001	-0.009	0.0002	0.002	-0.0007	-0.0003	0.0005	0.0002	0.0003
$\frac{\Delta MN}{MN}\frac{\Delta PLA}{PLA}$	-0.054	0.050	-0.011	-0.0009	-0.176	-0.038	-0.044	-0.063	-0.061	-0.056	-0.0004	-0.0005	-0.003	-0.011	-0.0003	-0.002	0.0007	0.0002	-0.001	-0.0003	-0.0002
$\frac{\Delta RNI}{RNI}\frac{\Delta PLA}{PLA}$	-0.022	0.141	-0.0008	0.003	-0.136	-0.039	-0.021	-0.025	-0.026	-0.021	0.036	-0.001	0.004	-0.015	0.0002	0.002	-0.0007	-0.0003	-0.002	0.0003	0.0003
Status Deck Inputs	1	$\frac{\Delta N1}{N1}$	$\frac{\Delta T6}{T6}$	$\frac{\Delta P2}{P2}$	$\frac{\Delta T2}{T2}$	$\frac{\Delta po}{po}$	$\left(\frac{\Delta N1}{N1}\right)^2$	$\left(\frac{\Delta T6}{T6}\right)^2$	$\left(\frac{\Delta P2}{P2}\right)^2$	$\left(\frac{\Delta T2}{T2}\right)^2$	$\left(\frac{\Delta po}{po}\right)^2$	ΔN1/N1 x ΔT6/T6	ΔN1/N1 x ΔP2/P2	ΔN1/N1 x ΔT2/T2	ΔN1/N1 x Δpo/po	ΔT6/T6 x ΔP2/P2	ΔT6/T6 x ΔT2/T2	ΔT6/T6 x Δpo/po	ΔP2/P2 x ΔT2/T2	ΔP2/P2 x Δpo/po	ΔT2/T2 x Δpo/po
VAR ± percent	0.001	0.136	0.007	0.003	0.013	0.002	0.005	0.002	0.001	0.003	0.007	0.004	0.002	0.013	0.000	0.001	0.005	0.000	0.003	0.000	0.000

*Variation from M = 1, RNI = 0.9, PLA = 78

Table 4. Continued

d. Stability: High Compressor Pressure Ratio

ΔPRH/PRH = f(ΔN1/N1, ΔT6/T6, ΔP2/P2, ΔT2/T2, Δpo/po), percent

	C_i = f(ΔMN/MN, ΔRNI/RNI, ΔPLA/PLA), percent																				
	C_0 +	C_1 +	C_2 +	C_3 +	C_4 +	C_5 +	C_6 +	C_7 +	C_8 +	C_9 +	C_{10} +	C_{11} +	C_{12} +	C_{13} +	C_{14} +	C_{15} +	C_{16} +	C_{17} +	C_{18} +	C_{19} +	C_{20}
Flight Cond, Power	0 002	0.011	1 04	0.002	-0.632	0.000	-0.032	-0.032	0.001	0.008	0.002	0.040	-0.002	-0.003	-0.001	-0 001	0 001	0 000	-0 001	0 001	0 000
$\frac{\Delta MN}{MN}$*	-0.005	-0 031	0.87	-0 001	-0 050	-0.001	-0.001	-0.002	-0.006	0.039	-0.006	-0.010	0.000	0 011	-0 004	-0.006	-0 010	-0 002	-0 004	0.003	-0 001
$\frac{\Delta RNI}{RNI}$*	0 000	0 029	0 057	-0 014	-0 017	0.004	-0 005	-0 002	0 000	-0.001	-0.001	-0.006	0.000	-0.003	0.005	0.002	-0.010	0 003	0 022	-0 005	0 004
$\frac{\Delta PLA}{PLA}$*	0 007	-0 074	0 032	-0.003	0 025	-0.002	-0 006	-0.006	0 002	0 002	0 002	0 009	0 000	0 002	-0.004	-0 005	0 006	-0 003	-0 002	0 003	-0 002
$\left(\frac{\Delta MN}{MN}\right)^2$	-0 008	0 026	-0 086	0 000	-0 042	0.000	0.004	-0 006	-0 008	0 046	-0 009	0 001	0.000	-0 001	-0.002	0 000	0 003	0 000	-0 001	0 002	0 000
$\left(\frac{\Delta RNI}{RNI}\right)^2$	0 001	-0 048	-0 046	0 012	-0 087	0 000	-0 001	-0 002	0 001	-0.020	0 001	0.006	0 001	-0 009	0 001	-0 007	0 014	0 000	0 001	-0 001	0.000
$\left(\frac{\Delta PLA}{PLA}\right)^2$	0 007	0 061	-0 042	-0.001	0 057	-0 001	0.005	0.010	0 002	-0 01[illegible]	0 002	-0 011	0.000	0.005	-0.001	0.001	-0.004	-0 001	-0 002	0 000	-0 001
$\frac{\Delta MN}{MN}\frac{\Delta RNI}{RNI}$	0 000	-0.033	-0.087	-0 001	0.008	0 004	-0 002	0.000	-0 002	-0 007	-0 002	-0 009	0.004	-0 007	0.006	0.006	0 000	0 003	0 006	-0 005	0 007
$\frac{\Delta MN}{MN}\frac{\Delta PLA}{PLA}$	0 002	-0.014	0 075	0.000	-0 045	-0.003	0 001	0.005	0 004	0.006	0 003	-0 006	-0 001	0.006	-0.004	-0 007	0 000	-0 004	-0 005	0.004	-0 005
$\frac{\Delta RNI}{RNI}\frac{\Delta PLA}{PLA}$	0 001	-0 008	0.045	0 007	-0 051	0.005	-0.004	-0.002	0.001	-0 00[illegible]	0.001	-0.004	0 004	-0 003	0.006	0 006	0 002	0 003	0 007	-0 006	0 006
Status Deck Inputs	1	$\frac{\Delta N1}{N1}$	$\frac{\Delta T6}{T6}$	$\frac{\Delta P2}{P2}$	$\frac{\Delta T2}{T2}$	$\frac{\Delta po}{po}$	$\left(\frac{\Delta N1}{N1}\right)^2$	$\left(\frac{\Delta T6}{T6}\right)^2$	$\left(\frac{\Delta P2}{P2}\right)^2$	$\left(\frac{\Delta T2}{T2}\right)^2$	$\left(\frac{\Delta po}{po}\right)^2$	ΔN1/N1 x ΔT6/T6	ΔN1/N1 x ΔP2/P2	ΔN1/N1 x ΔT2/T2	ΔN1/N1 x Δpo/po	ΔT6/T6 x ΔP2/P2	ΔT6/T6 x ΔT2/T2	ΔT6/T6 x Δpo/po	ΔP2/P2 x ΔT2/T2	ΔP2/P2 x Δpo/po	ΔT2/T2 x Δpo/po
VAR, ± percent	0 000	0 002	0 009	0 000	0.033	0.000	0 000	0.000	0.000	0 002	0.000	0 000	0.000	0 000	0 000	0 000	0 000	0.000	0 000	0.000	0 000

*Variation from M = 1, RNI = 0 9, PLA = 78

Table 4. Continued
e. Durability: Turbine Inlet Temperature
ΔT4/T4 = f(ΔN1/N1, ΔT6/T6, ΔP2/P2, ΔT2/T2, Δpo/po), percent

	Ci = f(ΔMN/MN, ΔRNI/RNI, ΔPLA/PLA), percent																				
	C_0 +	C_1 +	C_2 +	C_3 +	C_4 +	C_5 +	C_6 +	C_7 +	C_8 +	C_9 +	C_{10} +	C_{11} +	C_{12} +	C_{13} +	C_{14} +	C_{15} +	C_{16} +	C_{17} +	C_{18} +	C_{19} +	C_{20} +
Flight Cond. / Power	-0.001	0 370	0.727	0.001	0.035	0.000	0.018	-0.002	-0.002	-0 002	-0.001	-0.005	-0.002	0.013	-0 001	0.001	0.007	0.001	0 000	-0.002	-0.002
$\frac{\Delta MN^*}{MN}$	-0.005	-0.019	0.003	0.000	-0 011	-0 000	-0.012	-0.008	-0.006	-0 008	-0.006	0 003	0.000	0.009	0.000	0.000	0.000	0 000	0.000	0.000	0.000
$\frac{\Delta RNI^*}{RNI}$	0.000	0 007	0.004	-0 010	-0.002	-0 002	-0 020	-0 004	-0.001	-0.008	-0.000	-0.008	-0.009	0.012	-0 003	0.000	0.014	0.003	0 005	-0.003	-0.002
$\frac{\Delta PLA^*}{PLA}$	-0.005	-0.015	-0 012	0 000	0.005	0.000	-0.003	-0 006	-0.007	-0.007	-0.006	0 000	0.001	0.001	0.000	-0.001	0.002	0 000	0.001	0.000	0 000
$\left(\frac{\Delta MN}{MN}\right)^2$	0.000	-0.014	0 016	0.002	-0.024	0.000	0.002	0.003	0.000	0.006	-0.001	0.000	0.002	-0.024	0 000	0.001	-0.005	0.001	-0 003	0.000	0 000
$\left(\frac{\Delta RNI}{RNI}\right)^2$	-0.003	-0 044	-0.018	-0.010	0 018	0.003	-0.003	-0.009	-0 006	-0.014	-0.003	-0.012	-0.004	0.019	0.003	-0 007	0.007	-0.003	0 013	0.004	0.004
$\left(\frac{\Delta PLA}{PLA}\right)^2$	-0 001	-0.018	0.013	0.001	-0.010	-0.001	-0.011	-0.001	-0.001	-0 001	-0.002	0.004	0.001	-0.005	-0.001	0.002	-0.006	0.000	-0.004	0 000	0.000
$\frac{\Delta MN}{MN}\frac{\Delta RNI}{RNI}$	-0 002	-0.043	0.001	0.000	0.011	0.001	-0 008	-0.005	-0.004	-0 004	-0.004	0.001	0.001	0.002	0.000	0.000	0.000	0.000	0.000	0 000	0 000
$\frac{\Delta MN}{MN}\frac{\Delta PLA}{PLA}$	-0 008	-0.018	0 000	0.000	-0.017	0.000	-0.010	-0.010	-0.009	-0.010	-0.010	0.001	-0.001	0.001	0 000	0.001	0.002	0.000	0.000	0.000	0.000
$\frac{\Delta RNI}{RNI}\frac{\Delta PLA}{PLA}$	-0 002	0.001	-0.007	0.000	-0.008	0.000	0 003	-0.002	-0.003	-0.002	-0.002	-0.001	0.001	-0 006	0.000	0.000	0 000	0.000	-0 001	0.000	0 000
Status Deck Inputs	1	$\frac{\Delta N1}{N1}$	$\frac{\Delta T6}{T6}$	$\frac{\Delta P2}{P2}$	$\frac{\Delta T2}{T2}$	$\frac{\Delta po}{po}$	$\left(\frac{\Delta N1}{N1}\right)^2$	$\left(\frac{\Delta T6}{T6}\right)^2$	$\left(\frac{\Delta P2}{P2}\right)^2$	$\left(\frac{\Delta T2}{T2}\right)^2$	$\left(\frac{\Delta po}{po}\right)^2$	ΔN1/N1 x ΔT6/T6	ΔN1/N1 x ΔP2/P2	ΔN1/N1 x ΔT2/T2	ΔN1/N1 x Δpo/po	ΔT6/T6 x ΔP2/P2	ΔT6/T6 x ΔT2/T2	ΔT6/T6 x Δpo/po	ΔP2/P2 x ΔT2/T2	ΔP2/P2 x Δpo/po	ΔT2/T2 x Δpo/po
VAR, ± percent	0.000	0.002	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0 000	0 000

*Variation from M = 1, RNI = 0 9, PLA = 78

Table 4. Concluded

f. Durability: High Compressor Rotor Speed

$\Delta N2/N2 = f(\Delta N1/N1, \Delta T6/T6, \Delta P2/P2, \Delta T2/T2, \Delta po/po)$, percent

	$C_i = f(\Delta MN/MN, \Delta RNI/RNI, \Delta PLA/PLA)$, percent																				
	C_0 +	C_1 +	C_2 +	C_3 +	C_4 +	C_5 +	C_6 +	C_7 +	C_8 +	C_9 +	C_{10} +	C_{11} +	C_{12} +	C_{13} +	C_{14} +	C_{15} +	C_{16} +	C_{17} +	C_{18} +	C_{19} +	C_{20}
Flight Cond / Power	0.001	0.326	0.384	0.011	0.128	0.011	0.013	0.008	0.001	0.001	0.001	-0.028	0.015	-0.005	0.014	-0.014	0.006	-0.014	-0.014	0.015	-0.014
$\frac{\Delta MN}{MN}$*	-0.004	-0.010	-0.027	-0.003	0.004	0.002	-0.012	-0.014	-0.004	-0.007	-0.005	0.003	0.002	0.003	-0.001	0.003	-0.004	-0.004	0.001	0.002	-0.002
$\frac{\Delta RNI}{RNI}$*	-0.001	0.014	-0.011	-0.015	0.032	0.000	-0.006	-0.013	-0.003	-0.009	-0.001	-0.007	0.001	0.008	-0.002	-0.004	0.004	-0.003	0.008	0.003	-0.001
$\frac{\Delta PLA}{PLA}$*	-0.003	-0.003	0.080	0.000	-0.039	-0.003	-0.000	-0.008	-0.004	-0.004	-0.004	-0.001	-0.001	0.005	0.003	-0.003	0.001	0.001	-0.004	-0.003	0.002
$\left(\frac{\Delta MN}{MN}\right)^2$	-0.001	-0.021	-0.022	-0.002	-0.014	-0.002	0.005	0.001	-0.001	0.004	-0.002	0.009	-0.006	-0.013	-0.002	0.007	-0.001	0.004	0.002	-0.005	0.007
$\left(\frac{\Delta RNI}{RNI}\right)^2$	-0.002	-0.047	-0.043	-0.003	0.005	-0.007	-0.016	-0.006	-0.004	-0.011	-0.002	0.002	-0.011	0.022	-0.009	-0.001	0.003	0.010	0.008	-0.007	0.007
$\left(\frac{\Delta PLA}{PLA}\right)^2$	-0.002	-0.031	-0.056	-0.001	0.028	-0.003	-0.005	-0.000	-0.002	-0.001	-0.002	0.011	-0.005	0.001	-0.004	0.005	-0.005	0.006	0.004	-0.007	0.005
$\frac{\Delta MN}{MN} \frac{\Delta RNI}{RNI}$	-0.002	-0.052	-0.022	0.004	-0.009	-0.003	-0.005	0.007	-0.004	-0.007	-0.007	0.004	-0.005	0.004	0.003	-0.003	0.004	0.005	-0.004	-0.002	0.005
$\frac{\Delta MN}{MN} \frac{\Delta PLA}{PLA}$	-0.008	-0.008	-0.011	-0.002	-0.005	0.004	-0.011	0.001	-0.009	-0.010	-0.009	-0.005	0.003	-0.006	-0.005	0.005	-0.003	-0.003	0.005	0.006	-0.003
$\frac{\Delta RNI}{RNI} \frac{\Delta PLA}{PLA}$	-0.003	0.009	0.044	0.000	-0.007	0.004	0.000	0.009	-0.004	-0.003	-0.003	-0.006	0.002	-0.009	-0.006	0.006	-0.003	-0.003	0.006	0.005	-0.003
Status Deck Inputs	1	$\frac{\Delta N1}{N1}$	$\frac{\Delta T6}{T6}$	$\frac{\Delta P2}{P2}$	$\frac{\Delta T2}{T2}$	$\frac{\Delta po}{po}$	$\left(\frac{\Delta N1}{N1}\right)^2$	$\left(\frac{\Delta T6}{T6}\right)^2$	$\left(\frac{\Delta P2}{P2}\right)^2$	$\left(\frac{\Delta T2}{T2}\right)^2$	$\left(\frac{\Delta po}{po}\right)^2$	ΔN1/N1 x ΔT6/T6	ΔN1/N1 x ΔP2/P2	ΔN1/N1 x ΔT2/T2	ΔN1/N1 x Δpo/po	ΔT6/T6 x ΔP2/P2	ΔT6/T6 x ΔT2/T2	ΔT6/T6 x Δpo/po	ΔP2/P2 x ΔT2/T2	ΔP2/P2 x Δpo/po	ΔT2/T2 x Δpo/po
VAR, ± percent	0.000	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

*Variation from M = 1, RNI = 0.9, PLA = 78

NOMENCLATURE

ALT	Geometric altitude, ft
B	Bias error
DAY	Indicator for ambient temperature (Std, hot, etc.)
FN	Net thrust, lbf
K	Precision multiplier for uncertainty determination
M	Flight Mach number
N1	Low pressure compressor rotor speed, rpm
N2	High pressure compressor rotor speed, rpm
P2	Engine inlet total pressure, psia
PLA	Power lever angle, deg
PRH	High pressure compressor pressure ratio
po	Ambient static pressure, psia
RNI	Reynolds number index
S	Precision error
SFC	Specific fuel consumption, lbm/hr/lbf
T2	Engine inlet total temperature, °R
T4	Turbine inlet calculated total temperature, °R
T6	Turbine exit total temperature, °R
to	Ambient static temperature, °R
U	Uncertainty [$U = \pm(B + KS)$]
WA	Engine total airflow rate, lbm/sec